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HON. ERNEST F. HOLLINGS, *Chairman*

FOR THE USE OF THE

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

UNITED STATES SENATE

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LETTER OF TRANSMITTAL

U.S. SENATE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
Washington, DC, February 22, 1989.

DEAR COLLEAGUE: Last March, the Senate Committee on Commerce, Science, and Transportation asked the Congressional Research Service of the Library of Congress to conduct a workshop and prepare a report on the issues associated with the development of a high speed commercial transport. The Committee is pleased to submit the product of that effort, a report entitled "Commercial High Speed Aircraft Opportunities and Issues," for your consideration.

The Committee believes that this report highlights the issues central to the debate of a high speed commercial transport. Although the Committee will reserve its final judgment on the CRS workshop and the findings contained in this report until it has had an opportunity to conduct a series of hearings to further explore these matters, the Committee believes that the CRS report will serve as the basis for further exploration of this initiative by the 101st Congress.

The Committee notes that since it requested this report, the National Aeronautics and Space Administration has submitted a FY 1990 budget request for a new high speed commercial transport initiative. The focus of the first phase of this NASA initiative is environmental concerns—airport noise, sonic boom and ozone depletion. This reflects an awareness of the lessons learned from the SST debate of the 1970's and a sensitivity to the current concern about global change.

Realizing that the contribution of the aerospace industry is a critical element of the Nation's balance of trade and other foreign nations are actively pursuing development of a high speed commercial transport, the Committee intends to thoroughly assess this high speed commercial transport report and the FY 1990 NASA initiative. The Committee also intends to assess the relationship of the high speed civil transport initiative to sustained technological leadership in aeronautics and to the ongoing national aerospace plane research and technology program.

The Committee hopes that its colleagues find this report on high speed commercial transports a useful briefing paper as the Congress prepares to assess this important new initiative.

Sincerely,

ERNEST F. HOLLINGS,
Chairman.

LETTER OF SUBMITTAL

THE LIBRARY OF CONGRESS,
CONGRESSIONAL RESEARCH SERVICE,
Washington, DC, January 24, 1989.

HONORABLE ERNEST HOLLINGS, *Chairman*
SENATORS JOHN C. DANFORTH, DONALD REIGLE, JR., LARRY PRESSLER
Committee on Commerce, Science and Transportation, United States Senate, Washington, DC.

DEAR MR. CHAIRMAN AND SENATORS: In response to your joint request, we are forwarding a report entitled Commercial High Speed Aircraft: Opportunities and Issues.

This report examines the recent proposal by the National Aeronautics and Space Administration (NASA), made at the request of your Committee, to establish a research and technology program to develop and validate technologies needed for a high speed civil transport (HSCT). The report examines the technologies needed for such an aircraft to be economically competitive and environmentally acceptable. It also analyzes the environmental, market and air traffic system issues that an HSCT research and technology program would have to contend with. Finally, the report presents policy considerations for carrying out a research and technology program and for possible follow-on programs to develop a commercial HCST, and options for congressional action.

The CRS report was written by Richard Rowberg and Ms. Kathleen Hancock (currently at the General Accounting Office) of our Science Policy Research Division, and Christopher T. Hill, CRS Senior Specialist in Science and Technology Policy. In addition, material on the air traffic system was prepared by Kevin Dopart and Len Wojcik of the Congressional Office of Technology Assessment. Much of the analysis is based on a May 1988 workshop sponsored by CRS in which representatives from industry, Government, academia and public interest groups participated. Finally, the report was extensively reviewed by these participants as well as other experts in the field.

I trust that this report will serve the needs of the committee as you review the NASA budget submission and consider the Federal Government's role in long term development of advanced commercial aircraft technology.

Thank you for the opportunity to assist your committee.

Sincerely yours,

JOSEPH E. ROSS,
Director.

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OVERVIEW

Development of high speed civil transport (HSCT) technology by the National Aeronautics and Space Administration (NASA) and the United States aerospace industry has been called for by many as part of a major program in aeronautics research and development to help the United States keep its world lead in the commercial aircraft market well into the next century. For a high speed civil transport to enter the market, however, it will need to meet strict limits on airport noise and sonic boom levels, add no significant damage to the atmospheric ozone layer, and be competitive with a new generation of efficient long haul subsonic aircraft. Technology exists today to build an HSCT, but it would not meet these goals. While there is now no way to determine in advance whether these goals can be met, NASA and industry officials are optimistic that an economically competitive, environmentally acceptable HSCT can be built. Further, analyses done for NASA show that if an HSCT can be developed which meets these economic and environmental goals, a substantial market will exist in the first decades of the next century. Development of this technology could lead to an HSCT fleet early in the next century that could improve substantially long haul, air transport productivity.

Developing an acceptable HSCT would present a difficult and potentially costly technical challenge to NASA and the U.S. aerospace industry over the next 10 to 20 years. To meet these challenges, NASA has developed a proposed cooperative government-industry, multiyear technology development and validation plan at the request of Congress. The objective of the NASA plan is to advance key technologies in hopes that the operating cost of a commercial HSCT would be well below that which could be achieved using today's technology. The NASA plan encompasses neither construction of a prototype nor demonstration of major component systems, but is predicated on industry proceeding from the validation phase to develop a commercial HSCT. Because success is not assured, however, a Federal research and technology program to attain these goals would be a risky venture.

If the United States is to maintain preeminence in commercial aeronautics into the next century, the Nation probably would have to undertake this technology development and validation plan alone, or at least as the dominant partner. It is possible for the United States to do this, and, while NASA has not yet given a projected cost of the research and technology (R&T) program, current estimates are that it would require about 1.5 to 2 billion dollars (including both government and industry contributions) and 10 to 12 years to complete technology validation.

Beyond this R&T program, industry now believes that a prototype aircraft must be built to demonstrate the new technology before it would make a commitment for commercial production.

Current estimates are that a prototype would cost between 5 and 10 billion dollars, but these costs are highly uncertain. As with the R&T program, no decision has been made yet about the construction of a prototype aircraft. Further, much of the industry now feels that commercial production of a high speed civil transport fleet probably would have to be carried out by an international consortium because of the aircraft's high cost and because other nations may demand some participation as a condition to operate within their territories. Nevertheless, many believe that in developing the prototype, Federal assistance would be necessary. Also, some feel international cooperation in HSCT technology development should be pursued.

Technology Considerations

The technology now exists—primarily as design, materials and engine knowledge and systems—to build a high speed civil transport (HSCT) that would have a greater range, capacity and speed than the Concorde. Such an HSCT would use technology developed by the U.S. SST program of the 1960s and the NASA supersonic cruise research program of the 1970s. Without further research and technology development, however, an aircraft using existing technology would very likely not be able to meet current and expected environmental regulations concerning airport noise and ozone layer protection, nor operate with a sonic boom level that would allow operation over populated areas. In addition, such an aircraft would not be able to compete economically with subsonic aircraft over those routes which would be served by an HSCT.

To meet these environmental and cost goals, therefore, at a minimum, a major research and technology program that focuses on propulsion systems, aerodynamics, structures and materials, and control systems probably would be needed. For propulsion systems, the target would be an improved variable cycle engine (VCE) using advanced materials that can provide considerably greater fuel efficiency over the entire range of flight speeds, and reduced emissions and noise levels compared with current VCE technology. In aerodynamics, the objectives are designs and technologies leading to greater efficiencies by substantially reducing drag at both subsonic and supersonic speeds. Advanced materials development—primarily polymer and metal matrix composites—will be important to allow for significant weight reduction while maintaining structural integrity and operation in high temperature environments. An important aspect of materials development will be the need for manufacturing technologies designed to hold down aircraft construction costs. System and control technology development is needed to operate the aircraft at optimum efficiency and to maintain safety.

The current NASA proposal calls for a research and technology program addressing a potential HSCT in the Mach 2 to 5 (two to five times the speed of sound) range. Current subsonic transports cruise at about Mach 0.85 and the Concorde at Mach 1.8. The technical challenges for an HSCT flying above Mach 4 are considerably greater than for one flying at Mach 3.5 or lower. Above Mach 4 standard hydrocarbon fuels cannot be used. Instead, fuels cooled to very low temperatures (liquid hydrogen or liquid methane) will be

needed in order to absorb much of the heat generated by air friction with the aircraft moving at those speeds. Similarly, materials requirements will be much more stringent. It is possible, however, that a Mach 4 to 5 aircraft would ease some environmental constraints imposed on aircraft flying between Mach 2 and 3, particularly if the former flies at considerably higher altitudes than the latter.

The National Aerospace Plane program (NASP), currently being conducted by NASA and the Department of Defense, is carrying out research on technologies for a transatmospheric vehicle with a design goal of flight up to Mach 25. The program's goal is an aircraft capable of flying directly from the ground into Earth orbit. While the NASP program eventually may evolve to a hypersonic (Mach 5 to 14 range) civil transport, the program has not yet started to explore this regime. As the NASP program is currently being conducted, much of the technology being developed in it probably will not be applicable to the development of any high speed civil transport program in the Mach 2 to 4 range. For an HSCT in the Mach 5 range, however, there is likely to be greater contribution from the NASP program, particularly with materials and engine technologies.

Environmental Considerations

Of the three environmental concerns, protection of the ozone layer appears to be the most limiting at this time. Analyses indicate that current damage to the ozone layer resulting from deposition of chlorofluorocarbons (CFC) and other gases will take a century or more to be repaired. Any significant emissions that could further deplete the ozone layer, such as nitrogen oxides from aircraft engines, will likely not be acceptable because of the potentially harmful environmental and health effects of further ozone depletion. Therefore, a prime objective of a propulsion system development plan for an HSCT will be to reduce emissions so as to do no more harm to the ozone layer. While such technology appears possible to many experts, it is not yet clear how it would affect HSCT operating costs. Also, some analysts are concerned that if fuel additives are used to reduce NO_x production, these additives may generate harmful emissions.

An important parallel program would be expansion of studies on the effects of HSCT emissions on the ozone layer and to make sure these studies are closely coordinated with other research efforts on the earth's atmosphere being carried out by NASA and other Federal agencies. To address the scientific and related policy questions about protection of the ozone layer, which is of global concern, it may be very desirable for the United States to maintain a leadership role in these efforts. Such leadership could help enhance acceptance worldwide of an HSCT developed primarily in the United States.

The current technology for HSCT engines—the variable cycle engine—is unable to meet stage three airport noise requirements (currently the most stringent). Current analysis indicates that these or even tighter standards could be met with future technology although doing so will be difficult. The noise pattern at ground

level for subsonic aircraft meeting stage three standards would differ from that of a supersonic aircraft meeting the same standard. There is concern, therefore, that while these noise targets may be met when the noise is integrated over the monitored region, the peak noise from an HSCT might exceed limitations. If this is the case, the Federal Aviation Administration may wish to consider alternative noise measuring procedures, although local concerns must be accommodated.

It is unlikely that sonic booms significantly greater than 1 lb./sq. ft. overpressure from an HSCT fleet would be acceptable in populated areas. This is the restriction under which the Concorde must fly. While in principle it is possible to design a Mach 2-3 HSCT which produces a sonic boom below 1 lb./sq. ft. at ground level, such designs now appear to be impractical with current or projected technology. Because it would fly at a much higher altitude, it may be possible to build a Mach 5 or above HSCT which produces an acceptable ground level sonic boom. The alternative of prohibiting supersonic flight over land or, at a minimum, populated regions, may impose substantial economic penalties because of the aerodynamic design compromises required to provide for efficient subsonic cruise at both supersonic and subsonic speeds.

Market Considerations

High speed commercial transport aircraft are intended to achieve two goals: reducing the costs of air transportation services and travel time for both passengers and freight over long (above 5000 km) routes. For a successful HSCT lower costs would result from the fact that a greater number of seat-miles would be deliverable each day compared with subsonic aircraft of the same capacity. This could occur even if the capital costs per seat and fuel consumption per seat-mile were higher for an HSCT than competing subsonic aircraft, assuming that maintenance and turn around times can be held acceptably low.

Current forecasts by NASA sponsored analyses show a very large market for an HSCT if it is environmentally and economically acceptable to the public. These assessments, however, assume that fare premiums are likely to be necessary and that these premiums would range from 15 to 75 percent over subsonic fares depending on seating class. At these premiums, these same assessments find that an HSCT may be economically competitive with subsonic aircraft for routes longer than 4000 km because of the time savings realized. The possibility that fare premiums will be needed, however, may be damaging to the prospects for an HSCT. The image of being an aircraft that is available only to those sufficiently well off financially to pay high fares could severely hamper the public's acceptance of an HSCT research and technology program. A target of no fare premium appears highly desirable.

If an HSCT must fly at subsonic speeds over land to comply with restrictions on sonic boom, the economics of the aircraft could be compromised. Whether this would prevent an HSCT from being economically competitive with subsonic aircraft is not yet clear. Some important routes that lie mostly over land—e.g., New York to Tokyo—could be precluded for an HSCT flying with sonic boom

restrictions. Since the HSCT will be an international carrier, access to foreign territories and airports is essential. This is likely to be an important determinant in considering international involvement in any HSCT production consortium.

Air Transport System Considerations

While upgrading the air transport system is of major concern in the United States—regardless of HSCT developments—improvements on a global scale are likely to be much less significant for the development and acceptability of an HSCT for international travel than the other considerations described above. One concern is the availability of fuel. Since an HSCT in the Mach 3 range probably will not use Jet A fuel—JP-7 fuel instead—new fuel storage and handling facilities would be needed at all airports served by an HSCT fleet. Such facilities would be considerably more costly if liquid hydrogen or methane were used (Mach 4 and above) than JP-7. Also, to minimize time loss due to unscheduled maintenance and repair, airlines would have to establish specialized repair facilities at several HSCT terminals.

The economics of an HSCT fleet would require that ground turnaround time be kept to a minimum. It would be important to the airlines operating HSCT aircraft that the international air traffic control system function more efficiently than it now does. Greater air traffic system efficiency is a major concern for the entire airline industry, however, and such steps may be taken even in the absence of an HSCT fleet. Indeed, the HSCT offers the hope of leveling departure and arrival peaks and allowing for improved destination weather prediction accuracy because of its much shorter flight times. Also, flying at a greatly expanded range of altitudes could reduce international air traffic control pressures compared to a situation where only subsonic aircraft operated.

Policy and Program Considerations

The primary issue for the Congress is whether to authorize a formal program for NASA to develop the research and technology base for a new generation of HSCT. The decision would require a balancing of the uncertain future benefits that would accrue to the nation if an HSCT can be built and operated successfully against the costs of the program in a time of budget constraint. The Congress may wish to take action on several items in their oversight responsibility should the HSCT program be approved. These include: obtaining a clear understanding of the assumptions and goals of the program, and any changes in them; carefully monitoring the interaction between the HSCT research and technology program and other, relevant activities such as research on the ozone layer, changes in the energy situation and analyses of projected market conditions; and initiating exploratory work on possible follow-on steps such as financial assistance mechanisms and international ventures.

Given the nature of the proposed NASA program—no major demonstrations of technologies or prototypes are planned—a precise definition of technology validation appears to be lacking. In particular, it would be important for NASA to clarify how it in-

tends to demonstrate that it has achieved the operating cost reduction goals which now seem to constitute the principal measure of validation.

The Federal budget pressures that now exist raise the possibility of severe competition with the space program for funds. This competition could be intensified if the Nation decides to expand space efforts to any extent. In addition, an HSCT program might also find itself in competition for personnel resources with other aeronautics programs such as the National Aerospace Plane and advanced subsonic aircraft.

The current proposal calls for NASA to lead a joint industry-government project as in past NASA (and NACA) projects. While industry feels that this organizational structure is the best way to carry out the HSCT program, the size and complexity of this proposal are such that it may be useful for the Congress to explore alternative cooperative research arrangements.

Beyond the research and technology program lie decisions about how to proceed to a commercial HSCT fleet if the goals of technology validation are met. It now appears that realization of a commercial HSCT fleet would require some type of government assistance. Most industry representatives believe that the development costs will be so high that no manufacturer would be able to recover them for any reasonable projection of fleet size. Some Federal assistance methods that have been suggested are a guaranteed government buy, government financing of the prototype and various financial incentives such as tax credits or guaranteed loans. At this time, no one method appears to offer clear advantages, although it is difficult to make an accurate assessment since so little is known about the eventual development costs of the aircraft.

An international consortium of aerospace firms is also a possibility for development of an HSCT fleet. Indeed, most industry representatives believe an international effort would be necessary because of the ultimate cost. Even with such a consortium, however, some government assistance appears to be necessary to proceed with the production stage.

INTRODUCTION

The objective of this report is to identify for Congress the issues surrounding a program on High Speed Civil Transport (HSCT)—a supersonic commercial aircraft which would fly at speeds two to five times faster than the speed of sound, over a range of about 10,000 km, and carry about 300 passengers. At the request of the Congress, the National Aeronautics and Space Administration (NASA) developed a proposed HSCT research and technology (R&T) program to validate the technology needed for the aircraft industry to reach a decision on whether to proceed with development and production of an HSCT. The NASA program proposal would cost $1.5 to $2.0 billion over ten to twelve years. According to NASA, this program would significantly lower the risks associated with development of an HSCT fleet through the research and validation of the technologies needed to meet environmental and economic requirements in the first decade of the 21st century.

This report begins with a general background, including a brief review of the aeronautics programs of the National Advisory Committee on Aeronautics (NACA) and its successor agency, the National Aeronautics and Space Administration (NASA). A brief history of supersonic aircraft programs since the 1950s is followed by a discussion of the renewed interest in high speed commercial aircraft and present congressional actions related to an HSCT program. The report then discusses key aspects of the proposed HSCT program: technology, environment, market, and the air transport system. Report sections for each of these four aspects contain background information followed by major issues, findings and uncertainties as identified by experts on HSCT and related issues. The final section focuses on policy and program considerations.

The background material is derived primarily from secondary sources, while the issues, findings and uncertainties, as well as the policy and program considerations, are based on a May 1988 workshop sponsored by the Congressional Research Service. The workshop participants included representatives from industry (airframe and engine manufacturers and airlines), government, academia, and public interest groups. The list of workshop attendees is included in Appendix A.

As part of its examination of the feasibility of an advanced program of R&D related to HSCT technology, in 1986 NASA let two, 3-phase study contracts to Boeing Aircraft and McDonnell Douglas. Each has examined the state of readiness of HSCT technology, alternative design concepts, environmental issues, and economic and market issues. CRS staff had access to formal briefing materials of the Phase II results delivered to NASA, and the persons responsible for these studies in the two companies were active participants in the May 1988 workshop.

GENERAL BACKGROUND

Review of NACA/NASA Programs on Aeronautics

A long history of research and study precedes the current congressional interest in high speed transport. NASA, and before 1958, the National Advisory Committee on Aeronautics (NACA), has long been involved with the U.S. aerospace industry to advance aeronautics technology in this country. This section reviews these past efforts, and current international activities in high speed civil transport.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NACA was created by the Congress in 1915 "to supervise and direct the scientific study of the problems of flight with a view to their practical solution, and to determine the problems which should be experimentally attacked and to discuss their solution and their application to practical questions." [1]

NACA consisted of numerous technical subcommittees and a Main Committee, which was responsible for policy and determining the direction of NACA's research efforts. Representatives of government, academia and industry held positions on the subcommittees and Main Committee. Through the formal committee structure as well as informal communications, NACA responded to industry's research requirements, gaining a reputation for working closely and efficiently with the companies it was meant to serve.

Although initially operating only in an advisory capacity, NACA eventually constructed three research laboratories: Langley (1920—Hampton, VA), Ames (1940—Sunnyvale, CA) and Lewis (1943—Cleveland, OH). Along with its federally funded in-house research, NACA conducted research directly for industry on a cost reimbursable basis often using the customer's research models. NACA was given the authority to make test results available to the Government and, if NACA determined that it was in the national interest to do so, to release the results to the public. This last provision was revised in 1949 to state that NACA would not release the research results to the public, except by specific agreement with the industrial sponsor.

NACA's research was directed toward the fundamentals of flight and therefore often applied to both commercial and military aviation. Among its major activities, NACA was involved in developing the engine cowling, instruments for measuring aerodynamic loads on aircraft, mechanisms for increasing control and maneuverability

[1] For a detailed history of NACA, see Roland, Alex, Model Research, Washington, U.S. Govt. Print. Off., 1985.

of high-performance aircraft, improvements in propeller design, and a diesel engine for aircraft.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

With the advent of satellites and space flight in the late 1950s, it became clear that NACA's structure and mission required major change. The launching of Sputnik was the impetus for the 1958 National Aeronautics and Space Act which dissolved NACA and created NASA. While NASA is authorized to form advisory committees, the permanent Main Committee and the subcommittees of NACA were discontinued.

According to the 1958 Space Act, NASA activities are to have one or more of the following objectives: expansion of knowledge of the atmosphere and space; improvement of aeronautical and space vehicles; development and operation of space vehicles; long-range studies of the benefits of aeronautical and space activities; preservation of the U.S. leadership in these areas; transfer of relevant information to other government agencies; cooperation with other nations; and effective utilization of scientific and engineering resources. The Space Act gave NASA authority to cooperate with industry and other institutions in research and technology development.[2]

In addition to the Supersonic Cruise Research program outlined in section II–B of this report, recent NASA programs in aeronautics include the Variable Cycle Engine, Advanced Technology Transport, and Aircraft Energy Efficiency programs. These and other programs cover research in areas such as composite materials, active flight control systems, aerodynamic design to reduce drag, and advanced turboprops. The fiscal year 1990 budget request for Aeronautical Research and Technology, under which these programs are funded, is $462.8 million out of a total NASA budget request of $13.2 billion.[3]

Review of U.S. Supersonic Transport Development

Interest in supersonic flight increased markedly after World War II.[4] In 1947, a U.S. Air Force Bell X–1 experimental aircraft became the first manned aircraft to exceed the speed of sound (Mach 1). Soon after, single engine military and test aircraft were routinely flying in the Mach 2 range, and in 1956 the B–58 bomber, which could reach speeds of Mach 2, was built. That event marked the start of serious interest in building a large aircraft that could cruise (extended flight) in the Mach 2 to 3 range, and in 1957, the U.S. Air Force began development of the B–70 bomber designed to cruise at Mach 3. Because of changing priorities in U.S. strategic military policy, however, the B–70 never went into production. In parallel, a supersonic cruise reconnaissance plane, the "Blackbird" (A–11, YF–12 and SR–71), was being developed for the Central Intelligence Agency and the U.S. Air Force.

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[2] Paul Dembling, private communication.

[3] U.S. National Aeronautics and Space Administration. Budget Estimate, Fiscal Year 1990. Washington. p. AS–7.

[4] McLean, Edward F. Supersonic Cruise Technology. National Aeronautics and Space Administration. NASA SP–972. Washington, 1985. p. 9.

The technology developed during the B–70 program spurred interest in developing a supersonic cruise transport (SST) for civilian applications.[5] In 1963, the United States announced a major SST research and development program.[6] In addition to the supersonic flight technology exemplified by the B–70 developments, the proposed U.S. SST program was stimulated by the great commercial success of subsonic jets and the beginning of SST development programs in the Soviet Union (the TU–144) and Europe (the French and British Concorde). Information obtained during development of the SR–71 was also made available to help support the civilian effort through agreements with the Air Force.

Although there was much enthusiasm at the start of the SST program, serious problems appeared almost at once.[7] These included the absence of significant information from military sources (the B–70 program had been cancelled and security constraints slowed technology transfer from the SR–71 program), a lack of interest by the airlines because of their heavy investment in subsonic jet aircraft, the need for major Federal funding because the cost of development was beyond the capabilities of any one airframe manufacturer, and major technical challenges to meet severe cost and environmental goals.

Nevertheless, a program was started in 1963 under the direction of the Federal Aviation Administration (FAA).[8] The program was designed to be a two or if necessary, three phase effort. The first phase was a design competition that either would result in a winning design for a prototype or would require a further competition (phase II) between two finalists if a clear winner could not be determined. The last phase was to be development of a prototype aircraft. Eventually, the design by Boeing (for the airframe) and General Electric (for the engines) was selected as the winner, and the two companies were contracted to develop a prototype.

The design aircraft, the Boeing 2707–300, was considerably more complicated than the TU–144 and the Concorde because the United States chose to develop a larger (187 passenger) and faster (Mach 2.7) aircraft. In addition, management of the program was made more difficult because of multiple agency involvement. As a result, delays in the prototype development program ensued. In addition, opposition to development intensified during the late 1960s on cost and environmental grounds. After much debate and an expenditure of about $1 billion (actual year dollars), the program was terminated by the Congress in 1971.[9]

Although the SST program was ended, interest continued in both the Congress and the Administration for further development of supersonic cruise transport technology. This interest was motivated primarily by a desire to keep this Nation abreast of SST technology developments in the event of major new initiatives by the Soviets or the Europeans. At the time, it was reasonably clear that neither the TU–144 nor the Concorde would be an economic success. In

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[5] Ibid., p. 12.
[6] U.S. Congress. Office of Technology Assessment. Impact of Advanced Air Transport Technology; Part 1: Advanced High-Speed Aircraft. OTA–T–112. Washington, Apr. 1980. p. 28.
[7] McLean, op. cit., p. 14.
[8] Ibid., p. 16.
[9] OTA, op. cit., p. 31.

1972, NASA proposed a research program aimed at addressing the important cost, performance and environmental problems.[10] The program, called the Supersonic Cruise Research (SCR) program, lasted from 1973 to 1981. In FY 1974, the administration requested $46 million for the SCR program, which was cut by the Congress to $10.1 million. Annual expenditures ranged from $8 to $11 million for the remainder of the program.

In 1979, at the request of the House Committee on Science and Technology, NASA developed a supersonic transport technology validation plan focused on propulsion, airframe and aircraft systems technology.[11] This validation program was designed to expand the SCR program so that technology development would reach a point that would allow the airframe and engine manufacturers to decide on further development of an advanced supersonic transport. The validation program was to cost $662 million (1981 dollars) over an eight year period. No initiatives emerged from this NASA effort, however, and in 1981 the SCR program itself was cancelled because of budget constraints and lack of interest by the airline industry.

The end of the SCR program meant the end of research specifically associated with civilian supersonic aircraft. Research continued, however, into technologies that are important to high speed civil transport (HSCT).[12] NASA has supported and continues to support work in propulsion systems, materials and aerodynamics that is relevant to an HSCT. Although there is no specific HSCT program, NASA estimates that it spent $10 to $15 million in FY 1988 on these technologies.

Current HSCT Activities

In 1985, an interagency group under the direction of the White House Office of Science and Technology Policy (OSTP), issued a report on the state of aeronautics research in the United States.[13] As a result of that report, an Aeronautical Policy Review committee was established to set R&D goals for maintaining the U.S. lead in aeronautical technology. In March 1985, a report was issued stating R&D goals for subsonic, supersonic and transatmospheric aircraft. The Review Committee found that "U.S. national aeronautical policy now stipulates that the nation cannot and will not allow [aeronautical] leadership erosion." [14]

In February 1987, the OSTP issued another report setting out an action plan to meet the goals set forth in the earlier report.[15] The action plan described technology needed to develop a new generation of fuel efficient subsonic aircraft, an economically competitive and environmentally acceptable supersonic aircraft, and the construction of an experimental research plane (the X-30 National

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[10] McLean, op. cit., p. 19.
[11] OTA, op. cit., p. 34.
[12] U.S. National Aeronautics and Space Administration. NASA Aeronautics: Research and Technology. EP-259. Office of Aeronautics and Space Technology. Washington, 1987. p. 14.
[13] Executive Office of the President. National Aeronautical R&D Goals: Technology for America's Future. Office of Science and Technology Policy. Washington, Mar. 1985.
[14] Ibid., p. 1.
[15] Executive Office of the President. National Aeronautical R&D Goals: Agenda for Achievement. Office of Science and Technology Policy. Washington, Feb. 1987.

Aerospace Plane or NASP) that could operate outside the earth's atmosphere. The report also spelled out research needs to improve the Nation's air transport system, and indicated the proper role for NASA and other Federal agencies under each major goal. In particular, the report recommended that NASA, along with DOD and industry, emphasize validation of the important technologies needed for these future aircraft.

As a follow-up to the OSTP report, in its report on the FY 1987 NASA authorization bill, the Senate Committee on Commerce, Science and Transportation directed NASA to "prepare a multi-year technology development and validation plan that will help the United States retain its leadership in aeronautics research and technology. . . ." [16] The Committee's concerns centered on the civil aircraft portion of the OSTP proposals, namely subsonic and supersonic aircraft technology development and validation. Responding to the Committee's directive, NASA prepared a civil aeronautics technology development and validation plan that was released March 1988.[17] The plan addresses technology for three civil aircraft markets: subsonic transport, civil tiltrotor commuter aircraft, and high speed civil transport (HSCT).

The NASA report emphasized the importance of maintaining or enhancing U.S. leadership in each technical area. The OSTP and NASA reports have pointed out the large trade surplus currently enjoyed by the United States in aeronautics and the importance of a strong research and development program for sustaining that balance in the face of increasing international competition. Indeed, evidence of renewed European and Japanese interest and research efforts in high speed aircraft has been a major factor in stimulating U.S. interest in reviving an HSCT program in this country. Proponents of a U.S. HSCT program are concerned that these foreign competitors will develop a commercial supersonic transport before this country and that we will lose our lead in commercial aircraft sales. Some opponents, however, believe that an environmentally acceptable HSCT cannot be built, and that the concern about foreign competition is, therefore, misplaced.

Although not directed toward a supersonic civilian aircraft, the national aerospace plane (NASP) program bears some relation to the current interest in HSCT.[18] The goal of the NASP program is an experimental aircraft that can take off horizontally, reach speeds of Mach 25 and attain low earth orbit. The program also calls for a plane capable of traveling in the earth's atmosphere at hypersonic speeds of Mach 5 to Mach 14. With these performance goals, the NASP is an enormous technical challenge requiring, among other things, complex hybrid propulsion technology, development and fabrication of advanced materials, and the solution of very difficult hypersonic flow problems.

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[16] U.S. Congress. Senate. Committee on Commerce, Science, and Transportation. NASA Authorization Act, 1988. Report, 100th Cong., 1st, Sess., on S. 1164, June 24, 1987. Washington. p. 61.

[17] U.S. National Aeronautics and Space Administration. Civil Aeronautics Technology Development and Validation Plan. Office of Aeronautics and Space Technology. Washington, Mar. 1988.

[18] Testing the Limits at Mach 15. Science, v. 240, May 20, 1988.p. 973.

Although the original announcement of NASP in 1986 created some confusion about possible civilian transport applications, the current NASP program does not offer such for the foreseeable future.[19] Rather, the NASP may enable new military applications and could lower space launch costs. The first NASP is scheduled to begin research flights in 1995. The cost of the research program is currently estimated to be $3.3 billion, of which nearly $500 million has been spent.[20] While there is little relationship between the NASP and an HSCT in the Mach 2–4 range, some of the technologies developed for the NASP may be applicable. The potential applicability could be significantly greater for an HSCT in the Mach 5 range. In addition, the NASP program has contributed to the renewed interest in an HSCT and has helped maintain active research into high speed flight after the end of the SCR program.

International Activities

At the turn of the century, British Airways and Air France are expected to end operations of their 13 Concorde aircraft that have been flying commercially since 1976. When development costs are included, the Concorde has not been a financial success, although revenues currently exceed operating costs and the aircraft enjoys considerable popularity with certain classes of international travelers. While a major effort to develop a follow-on to the Concorde is not now underway in either Britain or France, there is activity in many of the industrialized countries to explore several possibilities for high speed civil transport in the period after 2000.

The French currently have a modest research effort on a second generation Concorde, while Britain and Germany have programs oriented toward aerospace planes. Since the technologies required for a commercial aircraft are significantly different from those for an aerospace plane, it is uncertain how applicable the British and German programs are to the development of an HSCT. Although it has limited experience in air transport production, Japan is performing research on the technologies necessary for supersonic aircraft. And, the Soviet Union is apparently working on a supersonic aircraft fueled with liquid hydrogen. Below is a more detailed country-by-country look at current international HSCT activities.

BRITAIN

With the support of the British government, British Aerospace and Rolls Royce have studied and performed research on a project called HOTOL (Horizontal Take Off and Landing) which would be an automated transatmospheric vehicle which could carry people. This concept is being considered primarily as a competitor with future American and European space transportation systems. The British government, however, recently withdrew its backing.[21] Private developers are considering modifications to HOTOL to permit its use as a commercial passenger vehicle, although their efforts

[19] Ibid.
[20] Ibid., p. 974.
[21] British Government Refuses to Back Phase 2 HOTOL Research Effort. Aviation Week & Space Technology, v. 129, no. 6, Aug. 1, 1988, p. 19.

have been reduced significantly following withdrawal of British government support.

FRANCE

In France Aerospatiale has financed a series of Avion de Transport Supersonique Futur (ATSF) projects—ATSF-1 (1978), ATSF-2 (1980), ATSF-3 (1986) and currently ATSF-2000—to investigate a next generation supersonic transport. The ATSF would be a follow-on to the Concorde and would cruise at a speed between Mach 1.8 and 2.2. The ATSF currently is intended to carry approximately 200 passengers, have a range of 11,000 km, and meet what the French project to be 1990 airport noise requirements. Aerospatiale is also considering an even faster aircraft called Avion a Grande Vitesse (AGV). The AGV would be a Mach 4 or 5 aircraft, carrying 150 to 200 passengers, with a range of 13,900 km and a propulsion system based on a turbo/ramjet engine using liquid methane fuel. Aerospatiale has performed initial wind tunnel studies.

GERMANY

In Germany, Messerschmitt-Boelkow-Blohm (MBB) is continuing studies on the Sanger Space Transportation System. Like the British HOTOL, Sanger would be primarily a space transportation system. Sanger is currently proposed to be a two-stage system. The first stage would be a hypersonic aircraft with turbo/ramjet propulsion. The second stage would be rocket-powered and would separate from the first stage at an altitude of at least 30 km. The first stage would then return to earth. MBB states that Sanger's first stage could be modified to serve as a commercial aircraft carrying 230 to 250 passengers with a cruise speed of Mach 4 to 5.

JAPAN

Japan is considering two types of advanced aircraft. One would be for commercial, manned flight, and the other for unmanned flights into space. The Japanese Science and Technology Agency National Aerospace Laboratory (NAL) currently has 30 persons working on the project and the Finance Ministry has agreed to small budgets for fundamental research on a space plane. By 1990, Japan hopes to reach the technology evaluation stage.

The Japanese are considering Mach numbers anywhere between 2.5 and 5.0.[22] Under the Ministry of International Trade and Industry (MITI), the NAL and six private companies have begun concept definition. Kawasaki Heavy Industries and Mitsubishi Heavy Industries are jointly studying airframe designs, while Nissan Motor and Ishikawajima-Harima Heavy Industries (IHI) are developing concepts for a propulsion system. Fujitsu and Fuji Heavy Industries will research a flight control system and an unmanned vehicle demonstrator, respectively.

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[22] Japan Will Initiate Research on Supersonic-Hypersonic Transport. Aviation Week and Space Technology, v. 129, no. 21, Nov. 21, 1988. p. 61.

SOVIET UNION

The Soviet Union was the first country to fly a supersonic civil transport, the TU–144, in 1968. The aircraft, which was designed to fly at Mach 2.2 and carry 140 passengers a distance of 6,500 km went into production in 1972. An accident at the 1973 Paris Air Show, where the aircraft broke up just after takeoff, apparently stopped further development of the TU–144, although considerable uncertainty surrounded its subsequent status. Although few details are known about Soviet HSCT activity, they recently announced a study of a Mach 5 aircraft capable of carrying 300 passengers.[23]

In an experiment with implications for future HSCT development as well as for subsonic aircraft, the Soviets conducted a test flight of a liquid hydrogen-fueled (LH_2), commercial-size jet aircraft (the Tupolev-155) in April 1988[24]. There is considerable disagreement over the significance of this flight. While some have proclaimed the flight a major achievement, others have been more cautious, stating that the aircraft may have taken off on jet fuel and then switched to LH_2, a feat similar to a flight test the United States conducted in the 1950s.

[23] Ibid., p. 61.
[24] As reported in Hoffman, Peter. The Hydrogen Newsletter III. Apr. 1988. p. 1.

TECHNOLOGY NEEDS

Introduction

Technology development for high speed civilian transport has a long history. Currently operating supersonic cruise technology is represented by the Concorde and the SR-71 reconnaissance aircraft. Supersonic flight technology has improved considerably since the Concorde and SR-71—primarily as a result of the NASA supersonic cruise research program—but no cruise aircraft today incorporates these advances. While a high speed civil transport (HSCT) superior to the Concorde and flying at Mach 2 to 3 could be built using today's technologies, most observers feel that such an aircraft would not be economically competitive with the latest generation subsonic aircraft. In addition, an HSCT based on current technology probably would not be able to meet environmental restrictions for airport noise, sonic boom and ozone layer protection. Therefore, further technology development is necessary, and this is the objective of the proposed NASA program. This section presents an overview of the proposed technology needs and a discussion of the major areas of uncertainty.

Propulsion Systems and Fuels

TECHNOLOGY BACKGROUND

The propulsion system for an HSCT must be able to meet stringent economic and environmental goals. Current operating technology is the propulsion system used by the Concorde. This engine is a standard turbojet with an afterburner to provide the acceleration for reaching supersonic speeds. The efficiency of turbojets drops significantly at subsonic speeds. As a result, the Concorde has a much lower efficiency below supersonic (off-design) speed, than at its supersonic design speed. Poor off-design efficiency adds to the fuel requirements and, therefore, reduces the aircraft payload. With this in mind, the SCR program developed a variable cycle engine (VCE) which operates as a turbofan at lower speeds and as a turbojet at supersonic speeds by adjusting the airflow by means of variable inlets and nozzles.[25] The engine exit nozzle can also be varied thus greatly reducing engine noise. The engine has a high combustion efficiency and low NO_x emissions, compared with Concorde technology. These concepts have been built into an engine that has been tested on the ground. No flight testing has taken place.

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[25] McLean, Edward F. Supersonic Cruise Technology. National Aeronautics and Space Administration, NASA SP-472. Washington, 1988. p. 141.

While the variable cycle engine represents a substantial improvement over Concorde technology, much greater improvement appears necessary. In particular, overall fuel economy must be improved in order to reduce operating costs below those now possible. The actual target for fuel economy improvement, however, is not yet clear. Although the NASA proposal calls for a 30 percent reduction from current capabilities (see below), some industry experts believe that target cannot be reached nor that it is necessary to reach it in order to achieve an economic HSCT. Setting a "unrealistic" goal, they argue, could unnecessarily jeopardize the program. An important early task of an HSCT research and technology program would be a reexamination of the engine fuel economy goal.

An immediate objective of the proposed research and technology program is optimization of the VCE for overall operation in the subsonic, transonic and supersonic regimes. This would require higher performance materials and controls for nozzles, inlets and airflow valves.[26] The next step would be to develop an advanced core—the compressor, turbine and combustion chamber assembly—from high temperature and high strength materials. Such a core would allow higher operating temperatures and compression ratios, improving combustion efficiency. Research on inlet and nozzle design would also be important. Above Mach 2, the inlet and nozzle make important contributions to total thrust through compression of the incoming air and expansion of the exhaust gases.[27] Further, inlets and nozzles for an HSCT will weigh more than the engine core, adding to problems that would have to be overcome to improve aerodynamic efficiency. Research on improving inlet and nozzle efficiency could be as beneficial as research on the engine core in improving overall HSCT efficiency.

Beyond these steps, a supersonic throughflow turbofan could greatly increase propulsion efficiency.[28] Currently, the fans are able to operate only at subsonic flows. If the turbofan can operate at both subsonic and supersonic speeds, considerable weight and drag reduction can accrue. The reason is that the inlet system will be much less complex than a VCE. A critical element in all of these technology improvements would be the development of advanced materials combining high strength, high temperature resistance and light weight.

A final consideration with propulsion systems is improvement of off-design, or subsonic, efficiencies. A system that must operate at both subsonic and supersonic speeds will not operate at the lower speeds as efficiently as a strictly subsonic propulsion system. The off-design performance determines the acceleration efficiency of an HSCT and can be a major factor in setting the reserve fuel requirements for safe operation.[29] (Reserve fuel is the amount required to

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[26] U.S. National Aeronautics and Space Administration. Civil Aeronautics Technology Development and Validation Plan. Office of Aeronautics and Space Technology, Mar. 1988. p. 38.
[27] Lockheed Aeronautical Systems Co., private communication.
[28] Ibid., p. 38.
[29] Morris, S. J., Jr. et al. Propulsion System Issues for the High-Speed Civil Transport Study. AIAA Paper 87-2938, Sept. 1987. p. 4.

reach an alternate destination and to be able to hold there for landing clearance.) Since reductions in reserve fuel requirements lead directly to increased payload for a given size aircraft, it is important to keep the reserve fuel fraction (ratio of reserve fuel weight to gross vehicle weight) as low as possible. Finally, if an HSCT would have to operate subsonically for significant portions of its flight because of prohibitions on sonic boom over land, the off-design efficiency would be crucial for the aircraft's economics.

THE NASA RESEARCH AND TECHNOLOGY PROGRAM PROPOSAL

The NASA proposal calls for a research and technology (R&T) program to develop a propulsion system that uses 50 percent less fuel than Concorde technology and 30 percent less than 1988 technology resulting from the SCR program.[30] In addition, the system will have to meet noise requirements that are likely to be more severe than today's, and NO_x emissions requirements more severe than those imposed on current aircraft. The latter two conditions are discussed more completely in the section on environment. The program would build on the current R&T efforts within NASA with emphasis on development of high-temperature materials and on system studies. In addition, the base program would be expanded to include more research on supersonic throughflow fans, and to start research on variable geometry inlets, nozzles, valves and ducts. The latter effort is designed to develop a VCE with optimum efficiency.

NASA hopes to extend this program to development of components for a propulsion system and development of an advanced core for the VCE. NASA proposes to adapt core technology arising from the joint DOD/NASA Integrated High-Performance Turbine Technology (IHPTET) program.[31] The goal of the IHPTET program is doubling aeronautical propulsion capabilities by 2000. In carrying out this technology development program, NASA would emphasize low-emission combustion and low-noise exhaust nozzles.

The final stage of the NASA proposal calls for what NASA defines as validation of these propulsion technologies. This step would integrate the components coming from the technology development phase in order to verify control dynamics, system stability and performance of the advanced VCE, and to validate the supersonic throughflow fan concept. At this stage, NASA feels that the technology would be ready for full-scale engine development leading to certification. This validation step does not now call for construction of a prototype engine.

FUEL CONSIDERATIONS

In addition to propulsion system technologies, an important element of future HSCT operation is fuel choice. Currently, the fuel used by the Concorde is Jet A which is the standard fuel used by subsonic aircraft. An important function of the fuel is to act as coolant (heat sink) for components in the engine and aircraft by ab-

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[30] NASA, op. cit., p. 39.

[31] U.S. Dept. of Defense. Annual Report to the Congress. Fiscal Year 1989. Washington, Feb. 1988. p. 272.

sorbing heat prior to combustion of the fuel. As the speed of the aircraft increases above Mach 1, the heat generated by friction increases dramatically, and above Mach 2 to 2.5, the heat capacity of Jet A fuel is no longer large enough to provide adequate cooling.[32] Therefore, different fuels must be used. The most likely candidate is JP-7, a hydrocarbon capable of providing adequate cooling up to Mach 3.5 to 4.0. Beyond those speeds, special fuels are required. The most likely candidates are liquid methane and liquid hydrogen. The latter has by far the largest heat sink capability and would be useful up to Mach 6.5. It also has the highest energy content per pound (though not the highest per unit volume) of any of the candidate fuels. Liquid methane (LCH_4) and liquid hydrogen (LH_2), however, are cryogenic fuels; that is, they must be stored at very low temperatures so that they will remain liquid and not require very high pressure storage and transfer systems. Complex refrigeration systems are required to maintain them in the liquid state.

The current fuel of choice for an HSCT is JP-7. It is readily available and used routinely in the SR-71 and other military aircraft flying above Mach 2. Both liquid methane and liquid hydrogen systems would require additional development before economic, reliable use can be expected, although test aircraft have flown using liquid hydrogen.[33] Both liquid hydrogen and liquid methane are widely used in other industries, and technologies for producing and handling them are well established. For an HSCT, the challenges are to design absolutely leak-free fuel storage and handling systems—both ground based and on the aircraft—and to develop appropriate on board insulating materials and heat exchange devices.

A major advantage of LH_2 is that the combustion product is water vapor. Therefore, no harmful emissions would come from the fuel itself, although nitrous oxide emissions—those responsible for ozone depletion—would still be produced unless the combustion temperature was kept below the level at which these compounds form from atmospheric nitrogen. A major disadvantage of both liquid hydrogen and liquid methane is that, compared with Jet A and JP-7, they are less dense (more so for liquid hydrogen than liquid methane) and therefore require larger fuel tanks despite their higher energy content by weight. At this time, NASA has not included any specific studies of new fuel technologies in the proposed HSCT. If an HSCT technology program is to explore Mach numbers greater than 4, however, additional work on fuels will be necessary. In addition, there are safety considerations which are peculiar to the storage of cryogenic fuels. These are discussed more fully below in the section on the air transport system.

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[32] Morris, op. cit., p. 2.
[33] Clean Hydrogen Beckens Aviation Engineers. New York Times, May 24, 1988. p. C1.

AERODYNAMICS

TECHNOLOGY BACKGROUND

Aerodynamic improvements over current technology can result in cost reductions for a future HSCT as great as those possible for improvements in propulsion systems. The principal goal of the aerodynamic phase is to increase the flight efficiency of the aircraft—known as the lift to drag ratio (L/D)—for all phases of an HSCT's flight. Increasing L/D will result in increased range and payload for a given size aircraft.

A fundamental difficulty in improving L/D, however, is that the most efficient design for supersonic flight is not that for subsonic flight.[34] Current aerodynamic theory and data indicate that a highly swept wing provides the best L/D for supersonic cruise. This wing design will yield the least drag for a given amount of lift and air speed above Mach 1. For speeds near but below Mach 1, however, theory and experience shows that a moderately swept wing is the best design. Since an HSCT very likely will have to fly at subsonic speeds for extended periods—well beyond that needed to accelerate to supersonic speeds—subsonic efficiencies must be high. High subsonic efficiency is needed to keep the reserve fuel fraction low and to keep noise levels down.

The result of these conflicting requirements is that the overall design of an HSCT will represent a compromise. In fact, the first Boeing proposal under the SST program of the 1960s incorporated a swing wing design that would change sweep as the aircraft moved into the supersonic regime.[35] Boeing later dropped this proposal when it became clear that the mechanical complexity and weight penalty imposed by the variable wing were too great. Their final design incorporated a fixed delta-wing design. The Concorde also chose a swept-delta arrangement as the best compromise at the time. Further development of wing design, wing/fuselage integration, and engine placement permitted a potential increase in supersonic cruise efficiency of 25 to 30 percent, although these design changes were not incorporated into either the Concorde or the Boeing 2707-300 proposal.[36]

When the SCR program was initiated after cancellation of the SST program, the emphasis in aerodynamic research was placed on improving the off-design (subsonic) efficiency of the highly swept wing designs.[37] This was done through extensive analysis and wind tunnel tests. As a result of this program, new airfoil shaping and improved wing-body blending reduced drag significantly at subsonic speeds and yielded an L/D improvement of about 20 to 30 percent over the Concorde. This technology represents the current status of aerodynamic design for an HSCT.

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[34] McLean, op. cit., p. 80.
[35] Ibid., p. 16.
[36] Ibid., p. 51.
[37] Ibid., p. 123.

There are several areas where technology development could yield important improvements in L/D for both the subsonic and supersonic portions of an HSCT flight. First is the area of active controls. Nearly all commercial aircraft are statically stable. That is, the aircraft will return to equilibrium—as defined by the position of the aircraft, relative to the flowing air that keeps the aircraft aloft—once a perturbing force is removed, without any control action.[38] Statically stable aircraft are "forgiving" of pilot and mechanical errors, but at the price of more limited maneuverability. The advent of active controls that allow automatic adjustment of the flight control surfaces—ailerons, elevators and rudder—has allowed the design and construction of aircraft which are not statically stable and therefore more responsive.[39] In this case, control surfaces are activated fast enough and with sufficient precision to return the perturbed aircraft to equilibrium even though it might not do so in the absence of such control actions. Active controls require fly-by-wire or, possibly, fly-by-light systems. Hydraulic lines, now used on nearly all commercial aircraft would be replaced by wires (or fiber optic cables in the case of fly-by-light) which carry electronic (or optical) signals from the cockpit to hydraulic or electric powered actuators located at the control surfaces. Response times are greatly reduced by such systems. Some military aircraft—the F-16 and F-18 in particular—have active controls to help maintain flight stability. The principal advantage of active controls for military aircraft is to increase their maneuverability. It is possible that use of active controls would allow design of an HSCT with substantially greater off-design (subsonic) lift-to-drag ratios, but without complete static stability at these speeds.[40]

A second area of technical opportunity is laminar flow. Currently, the flow of air adjacent to the aircraft (the boundary layer) is usually turbulent, producing significant friction and drag on the aircraft. Reducing turbulence in the boundary layer between the air foil and flowing air reduces viscous drag, yielding a large increase in the lift-to-drag ratio.[41] The principal approaches to reducing turbulence are to shape the airfoil in such a way as to produce natural laminar flow—i.e., the absence of turbulence—or to create an active boundary layer control that will force laminar flow over all or part of the airfoil. These approaches are very difficult and require substantial modeling and experimentation. Improved wind tunnels are likely to be required. The payoff may be quite high, however, in that lift-to-drag ratio gains of 10 to 20 percent appear possible. These gains could result in reduced aircraft weight and sonic boom intensity. In addition, laminar flow can also significantly reduce skin and fuel temperature, which can have profound implications for materials and fuel selection.

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[38] Anderson, John D., Jr. Introduction to Flight, Second Edition. McGraw-Hill, 1983, p. 344-346.

[39] U.S. National Aeronautics and Space Administration. NASA Aeronautics Research and Technology, EP-259. Washington, 1987. p. 21.

[40] Swihart, John M. Aeronautical Developments for the 21st Century. AIAA Paper 87-3052, Sept. 1987. p. 12.

[41] Ibid., p. 14.

The third area of technical opportunity is an analytical tool, computational fluid dynamics (CFD), which would serve as a complement to wind tunnel and flight testing.[42] Using CFD, designers can calculate the detailed patterns of air flow, temperature and forces acting on an aircraft design, as well as the stresses and response of the design to operating conditions. Application of CFD requires substantial computing power and complex software. Hardware and software now exist, however, that allow simulation and analysis of full aircraft designs under conditions that are quite difficult to achieve in currently available wind tunnels. And despite its complexity and cost, the CFD approach can be much less expensive than building and testing models, mock-ups or prototypes.

THE NASA RESEARCH AND TECHNOLOGY PROGRAM PROPOSAL

The objective of the NASA program is to develop and validate technology to reduce aerodynamic drag compared to existing technology in order to improve the efficiency and range of an HSCT. The specific targets are a 60 percent increase in the lift-to-drag ratio compared with Concorde technology and a nearly 40 percent increase compared with 1981 SCR technology.[43] The areas of work would include development of boundary layer control technologies to reach laminar flow conditions wherever possible, reduction of skin friction by modifying the turbulent boundary layer, and reduction of drag resulting from the shock wave in the supersonic regime.

NASA is also seeking to reduce sonic boom overpressure by aerodynamic design that modifies the shape and size of the shock wave. It may be possible to reduce the intensity of the shock wave such that supersonic flight over populated areas would be allowed, thus avoiding the design compromise between subsonic and supersonic lift-to-drag ratios. Another key element of the NASA program plan is "configuration integration." More a design philosophy than a specific technology, this approach seeks to maximize the benefits of advances in the other areas—engine design, aerodynamics, active controls, reduced drag, and sonic boom reduction—by explicit consideration of the interactions among all of them as the overall aircraft design is developed.

The NASA plan to accomplish these objectives begins with development of supersonic laminar flow technology. In parallel, there would be analysis and testing of configurations designed to reduce sonic booms. Those technical developments showing the greatest promise would be selected for flight testing on modified existing aircraft. Use of a computational technique—computational fluid dynamics—developed for the National Aerospace Plane would be applied to the HSCT analysis throughout. Integration of airframe and propulsion systems would also take place using design analysis and wind tunnel testing. These configuration studies would also allow evaluation of propulsion, materials and flight systems technology development. Finally, these technologies would be validated

[42] Ibid., p. 15.
[43] NASA, op. cit., p. 41.

through flight testing of large scale subcomponents, probably on modified SR–71 or F–16XL aircraft.

Materials and Structures

TECHNOLOGY BACKGROUND

At the start of the SST program, the primary structural material for aircraft was aluminum which limited aircraft skin temperatures to below 500F.[44] Analysis showed that an SST flying at Mach 2.7 would have skin temperatures greater than that; therefore, other materials were needed. The B–70 used stainless steel, but the material of choice for an SST was titanium. The SST program launched a major effort to expand knowledge of titanium and associated manufacturing technologies. These efforts resulted in a much greater understanding about design variables, properties of titanium, and fabrication techniques. A consequence was that titanium has made major inroads as a structural material for low temperature, subsonic aircraft. Low cost methods of fabricating titanium were not available, however, and the fabrication costs continued to rise as the SST program progressed, contributing significantly to the large cost escalation. The Concorde, which used high strength aluminum, also experienced cost escalation because of high fabrication costs. (Flying at Mach 1.8 the Concorde skin was at a temperature for which aluminum was acceptable.)

In addition to materials properties, structural challenges facing the SST designers were much different from those for military aircraft.[45] In particular, cost was of prime importance for the SST; great emphasis was put on low weight and high efficiency; and the safety requirements were more stringent. In addition, the interaction between aerodynamic design and aircraft structure was quite complex since the aerodynamic forces on the aircraft during flight alter the shape of the aircraft and the change in shape, in turn, affects the magnitudes of the forces. Analyzing this interaction required powerful computational tools. Meeting these challenges resulted in significant advances in structural design and computational techniques.

After the termination of the U.S. SST program, work on materials and structures continued under the supersonic cruise research (SCR) program, although at a considerably lower level. A major advance was the development of a technique for forming titanium panels that resulted in considerably lower weight and cost compared with previous methods.[46] In addition, the SCR program launched investigation of fiber reinforced titanium, which promised considerable increase in the material's strength-to-weight ratio. Another product of the SCR program was a stable fuel tank sealant that would operate in the high temperature environment of supersonic flight.[47]

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[44] McLean, op. cit., p. 53.
[45] Ibid., p. 84.
[46] Ibid., p. 131.
[47] Ibid., p. 134.

Advances in polymer composites, particularly for aerospace applications, also have been substantial during the last few years.[48] These advances have given a major boost to rekindling interest in an HSCT. The primary candidate composite materials are carbon/graphite, aramids (e.g., DuPont's Kevlar) and high-stiffness glass fibers in a resin matrix. Fiber-reinforced, high temperature thermoplastics are also showing growing promise. These composite materials have much higher strength-to-weight ratios than the metals they replace and save up to 30 percent in weight. Some also show superior fatigue and corrosion resistance. In addition, composites have potentially lower manufacturing costs than metal structures because large, integral composite structures can be made as one piece rather than being fabricated from many pieces. Currently, some military aircraft use composites for as much as 15 to 20 percent of their structure, and the advanced tactical fighter now under development will have 40 percent of its structural components made from composites.[49] Among commercial aircraft, about three percent of the Boeing 767 structure consists of polymer composites. Some projections indicate that as much as 80 percent of the structure of commercial aircraft will be of composites by early in the next century.[50]

TECHNOLOGY DESCRIPTION AND NEEDS

The primary objective of technology development in structures and materials is to develop an aircraft that has the lowest possible unloaded weight and still is able to withstand the high stresses of supersonic flight. Weight is a major concern since it strongly affects aircraft economics. In the polymer and metal-matrix composite materials and structures category, new, high strength-to-weight materials must be developed to enhance the economic attractiveness of an HSCT. A principal area for improvement is increasing the temperatures at which polymeric composite materials can be used.[51] The current temperature limit for continuous operation of organic polymers is about 700F. While this is higher than the expected requirement for an HSCT operating below Mach 4, a higher temperature limit would allow a greater safety margin and increase reliability. If speeds above Mach 4 are desired and skin temperatures cannot be reduced sufficiently by laminar flow techniques, materials with higher temperature limits will be necessary.

The development of electrical and electronic materials capable of withstanding continuous exposure to the high temperatures found at supersonic cruise speeds also is important, particularly if cruise speeds above Mach 3 are desired. Since advanced electronic systems would be required for fly-by-wire performance (see below), the need for such materials will be especially crucial. Because of the susceptibility of electronics to high temperatures, the SR-71 was originally designed with fewer electronic systems and more direct

[48] U.S. Congress. Office of Technology Assessment. Advanced Materials by Design, OTA-E-351. Washington, June 1988. p. 83.
[49] Ibid., p. 23.
[50] Swibart, op. cit., p. 28.
[51] U.S. Congress. Office of Technology Assessment, op. cit., p. 91.

pilot control than the technology might have allowed for.[52] Such a design compromise is not likely to be permitted for an HSCT.

Other important target areas are development of low-cost fabrication processes and investigation of new fiber-matrix combinations that are stronger and more flexible, including aluminum and titanium matrix composites. Also needed are sealants and coatings that can operate in a high temperature, mechanically stressful environment.

In the structures area, further development of computational techniques that can integrate the HSCT aerodynamic requirements with materials and construction considerations is needed.[53] To hold down aircraft weight, designs that reduce required structural support are needed. If active controls are used to increase aerodynamic efficiency, the aircraft would have to accommodate additional mechanical stresses, which would call for greater strength without additional weight.

THE NASA RESEARCH AND TECHNOLOGY PROGRAM PROPOSAL

The goal of the NASA plan is a 30 percent weight saving over the Concorde and a 25 percent reduction compared to the 1981 SCR technology.[54] The focus of the program would be new materials including composites—both polymer and metal matrix—high temperature aluminum alloys and low density titanium. In addition, the program would develop new structural design concepts, processing and fabrication techniques for composite materials, and technologies for integrating aerodynamic and structural design.

The research and technology plan would focus on new polymer composites that could be used for temperatures beyond 600F, advanced aluminum alloys for the temperature range of 600 to 900F, and low density titanium for temperatures up to 1600F. This plan would call for acceleration of existing materials research efforts in NASA and would emphasize the commercial applications of high temperature materials under development for the National Aerospace Plane. In the structures area, the NASA plan would focus on high temperature structural concepts, structural analysis and test methods. In addition, efforts would be applied to processing and fabrication techniques that would be directed to reducing construction costs, particularly for composites. Finally, in the validation stage, the NASA program would develop large scale structural components of the kind that would be used on an HSCT. These components would make use of the materials, structural analysis, and processing techniques developed under the technology development phase.

Systems and Integration

TECHNOLOGY BACKGROUND

The systems technology for an HSCT includes flight and engine control systems, displays and navigational systems, and flight man-

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[52] Johnson, Clarence L., Some Development Aspects of the YF-12A Interceptor Aircraft, AIAA Paper No. 69-757, July 1969.
[53] NASA, op. cit., p. 13.
[54] NASA, op. cit., p. 43.

agement of the aircraft. During the SST program, advances in control technologies allowed some relaxation of static stability requirements, which permitted some structural weight reduction.[55] In addition, digital displays and advanced navigational systems developed for the SST have since found their way into the most recent generation of subsonic aircraft.

Under the SCR program, further developments of control technology allowed greater use of active controls to augment stability.[56] In addition, active controls were developed to permit suppression of unwanted vibrations without additional structural members. Another development was an active control system for the landing gear to reduce the forces on the aircraft upon landing, which also offers the potential for weight reduction.

TECHNOLOGY DESCRIPTION AND NEEDS

To achieve maximum efficiency for an HSCT, it will be important that all of the control systems—engine, flight, navigation—be integrated so that the performance level of each system can be adjusted to add to the overall performance of the aircraft.[57] For example, aerodynamic and engine control settings need to be integrated so that the engine operates at power levels needed to achieve the desired flight characteristics, and no higher.

Controls must operate faster and more precisely. Development of fly-by-wire and fly-by-light technologies will be important. As previously discussed, fly-by-wire makes use of electronic signals to drive actuators at the aircraft's control surfaces while fly-by-light use light signals.[58] In addition to greatly reducing response time, considerable weight and cost savings would be achieved.

Higher capacity, faster data acquisition and processing systems would be important for HSCT operation, particularly since it would fly in a much more hostile environment than subsonic aircraft.[59] In this connection, artificial intelligence systems also offer the promise of enhancing pilot control and increasing safety. Since the cockpit of an HSCT will have more limited window space than subsonic aircraft to minimize the probability of sudden depressurization, advanced sensors and displays to increase the pilots' ability to see are needed in order to enhance aircraft operations at high speeds and during landing. Another promising area for development is flat plate electronic display technology. By eliminating bulky cathode ray tubes, these displays offers considerable reduction in weight and space requirements in the cockpit area, while expanding the amount of data that could be displayed. Greater data display may be necessary because of reduced visibility, although care is needed to ensure that the added display does not "overwhelm" the crew.

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[55] Swihart, op. cit., p. 28.
[56] Ibid., p. 154.
[57] NASA, op. cit., p. 45.
[58] Swihart, op. cit., p. 27.
[59] NASA, op. cit., p. 45.

The primary goal of the NASA research and technology plan in the systems area is to develop control integration technology—flight controls, engines, inlets, autopilots, navigation and environmental controls—for the HSCT. As described above, the objective of such integration is to enhance efficiency by providing for optimum simultaneous performance of flight and engine controls. NASA expects to achieve a 5 to 10 percent increase in fuel savings over that possible with current technology.[60]

Also, the NASA R&T program would address advanced cockpit display technology, and data acquisition and processing technology to improve flight management. Flat plate displays and technologies to expand the visual field of the flight crew would be investigated for purposes of enhancing safety and efficiency. In the controls area, the emphasis would be on development of active control technology to allow relaxation of stability requirements and bring significant structural weight savings.

In meeting these research and technology objectives, NASA intends to apply recent work on control integration technology to studies of HSCT configurations, and to develop design criteria and methods of analysis. Next, the plan calls for design, construction, ground testing and flight evaluation of advanced flight management computer technology. Development of flat plate display technology and improvements in flight data acquisition technology—including data needed for zero visibility landings—would be undertaken. Active control technology development would involve analysis and testing of control designs, and simulation and wind tunnel testing of promising concepts. Finally, the NASA plan calls for validation of integrated systems technology in modified aircraft, and flight testing of advanced cockpit systems.

Major Issues, Findings and Uncertainties

In addition to the specific technical uncertainties and issues described above, there are overriding issues that would control the direction of a research and technology program.

While an HSCT could be built now, available technology would not permit the production of an economically and environmentally acceptable aircraft. For the environment, the major technological goals are to meet airport noise limits and prevent further damage to the ozone layer. Achievement of a sonic boom level low enough to allow supersonic flight over land would be highly desirable, but it is not now clear that attaining this goal would be necessary for a successful HSCT.

To reach these environmental goals will require considerable work on combustion systems to reduce harmful emissions and production of NO_x on exhaust nozzles to reduce noise, and on aerodynamics and structures to reduce sonic boom overpressure. For economic acceptability, the principal targets are weight reduction through the use of new materials and structural designs, more efficient propulsion systems, and aerodynamic designs and control sys-

[60] Ibid.

tems to permit efficient flight at both subsonic and supersonic speeds.

New materials—particularly polymer and metal matrix composites—offer the greatest promise for weight reduction and increased efficiency. Research on materials properties and manufacturing techniques is important to reaching this goal.

Propulsion systems appear to need considerable development to meet the environmental goals of reduced noise and emissions. Validation of propulsion system technology would be needed—quite probably including construction of a prototype, which is not now included in the NASA proposal—before airframe manufacturers would be confident about the ability to meet these goals.

The optimum cruise speed of the HSCT is still at issue. The NASA program proposal calls for investigation in the range of Mach 2 to Mach 5. Recent studies concluded that a Mach 3.2 limit provided the best near term option.[61] The technology to fly at Mach 3 and below is fairly well understood. The technology requirements are significantly more difficult and less well known for flying above Mach 4.[62] Primarily, different propulsion systems and fuels would be needed. Aircraft surface temperatures become much greater and the aircraft configuration requirements are different above Mach 4 than below Mach 3. In general, higher Mach numbers would mean greater technological challenges, which probably would delay introduction of a commercial HSCT.

There may be some environmental advantages to using the advanced fuels (probably liquid hydrogen) and flying at the higher altitudes required of a Mach 4 plus aircraft. The increase in technical complexity, however, could make the cost of such an aircraft prohibitive. It may be premature to decide on the speed of an HSCT until the relationship between Mach number and environmental and economic factors is better understood. The extensive range of technologies that would have to be investigated in a Mach 2 to 5 program, however, makes it important to come to some decision on the speed as soon as possible in order to contain the cost of the research and technology program.

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[61] Contractors Urge Further Research to Validate HSCT Technologies. Aviation Week and Space Technology. Oct. 17, 1988, p. 40.

[62] Morris, S.J., op.cit., p.2.

ENVIRONMENTAL ISSUES

Principal Environmental Concerns

The three primary environmental issues related to the HSCT are stratospheric ozone depletion, the sonic boom and airport noise. Many of the technical obstacles facing potential HSCT developers are based on the need to resolve these issues. Engine manufacturers will need to address the harmful effects of engine emissions on the ozone layer as well as the noise generated by supersonic aircraft engines. Airframe designers may need to sharply reduce the sonic boom produced by an HSCT through aerodynamic improvements.

In addition to the technical challenges posed by these environmental concerns, political considerations must be taken into account. Public concern over possible harmful effects to humans and animals from sonic boom was one of the major issues that decided the fate of the Supersonic Transport (SST) in the 1960s and 1970s. While sonic boom may once again be a major issue, the current political sensitivity to global ozone depletion may mean that protection of the ozone layer will replace sonic boom as the primary environmental concern in any public debate on commercial supersonic aircraft.

While public tolerance of sonic boom and potential ozone depletion is somewhat unknown, the operations of subsonic aircraft and the Concorde have provided considerable evidence on what various communities will tolerate in aircraft engine noise. Airport noise is likely to be a significant issue as communities continue to organize against all sources of airport noise. Resolution of Federal local noise standards for an HSCT combined with research to reduce ground noise are important priorities if an HSCT is to be a commercial success.

State of Knowledge

OZONE

While chlorofluorocarbons (CFCs) have recently been the focus of concern about ozone depletion, scientists have recognized since the early 1970s that nitrogen oxides (NO_x) [63] emissions from high altitudes aircraft operations can affect the ozone layer. NO_x emissions result from engine operation at high combustion temperatures; the higher the temperature, the more NO_x emissions. Considerable uncertainty remains about the impacts of aircraft-related NO_x emissions on the stratospheric ozone balance and on global climate. An HSCT in the Mach 2–3 range would fly at altitudes within the

[63] Nitrogen oxide (NO_x) refers to nitric oxide (NO) and nitrogen dioxide (NO_2), collectively.

stratospheric ozone layer. There is a consensus among those who are involved with proposals to develop an HSCT that further research is necessary to quantify the effects of an HSCT on the ozone layer, and on appropriate technology to prevent such harm.

Ozone (O_3) is found in small quantities in the atmosphere, with peak concentration in the stratosphere about 12 to 15 miles above earth. It is critical to the balance of environmental conditions that supports life. There are two principal concerns about altering the amount and distribution of stratospheric ozone. First, a depletion of stratospheric ozone would result in more biologically harmful ultraviolet radiation (UV–B) reaching the earth's surface, leading to an increased incidence of skin cancer. In addition, an increase in ultraviolet radiation may affect such critical elements of the biosphere as the productivity of the phytoplankton near the surface of the ocean, which would affect ocean productivity in general. Second, the heat balance of the earth might be altered, possibly leading to changes in regional temperature, wind and precipitation patterns.

The amount of atmospheric ozone reflects a dynamic balance between different production and destruction processes resulting from chemical reactions, with transport playing an important role in ozone redistribution. Anything altering these processes will result in a new equilibrium quantity of ozone. Forms of chlorine, bromine, hydrogen and nitrogen are catalysts known to accelerate the rate of destruction; a single reactive molecule of one of these catalysts can destroy thousands of ozone molecules. Since many of the gases which are precursors to these catalysts have long atmospheric lifetimes, ozone changes now taking place will persist for several tens to a few hundreds of years.

When the stratospheric ozone is depleted, more ultraviolet radiation reaches the lower stratosphere and upper troposphere causing reactions that enhance ozone production which can elevate ozone concentrations in the lower atmosphere. While the ozone layer depletion may abate at rates which differ depending on altitude, many scientists point out that "changes in the distribution of ozone may be an environmental concern even if the total amount of ozone doesn't change." [64]

Ozone concentrations in the stratosphere vary with longitude, latitude, time of day, season, solar sunspot cycle, and unusual events such as volcanic eruptions. Also, ozone concentrations differ considerably in the hemispheres. These natural variations must be taken into account when searching for trends in ozone content and the effects of emissions on the ozone.

In 1985, an "ozone hole" was discovered over Antarctica. The "hole", which had not been predicted, is a large reduction in the concentration of ozone in the lower stratosphere above Antarctica during its spring (September and October). Ozone depletion above Antarctica has been occurring each spring for the past decade, but did not become severe until the mid-1980s. Ozone depletion has been observed in the Arctic as well, although it is not at this time on the same scale and duration as that over the South Pole.

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[64] Wang, Wei-Chyung and Dak Sze. Coupled Effects of Atmospheric N_2 and 0_3 on the Earth Climate. Nature, 286, 1980. p. 589.

The Ozone Trends Panel, comprised of over 100 scientists from around the world, released a study in March 1988 on the state of the ozone. The panel concluded that CFCs are primarily responsible for the ozone trends in the southern hemisphere, that there is indeed a global decline in ozone, and that CFCs are by inference the general cause of this decline. The observed global decline at mid- and high latitudes in winter is larger than had been predicted by available models.[65]

The Vienna Convention for the Protection of the Ozone Layer was signed in 1985 by twenty countries plus the European Economic Community. The Convention describes the general obligation of nations to control activities that "have or are likely to have adverse effects" on the ozone layer and to cooperate in scientific programs to understand risks to the ozone layer better. The 1987 "Montreal Protocol on Substances that Deplete the Ozone Layer" would freeze CFC consumption at 1986 levels on July 1, 1989 and then cut CFC production by 50 percent by 1998. Twenty-four nations and the European Community signed the protocol and it will go into effect on January 1, 1989.

During the SST debate held in the late 1960s, possible consequences of supersonic aircraft emissions became a major public issue. Since that time, various Federal research programs were established to examine these possible consequences, notably the Climatic Impact Assessment Program (CIAP), the Climatic Impact Committee, the High Altitude Pollution Program (HAPP), and the Stratospheric Emissions Impact portion of NASA's Supersonic Cruise Research program.

CIAP, initiated by Congress and conducted by the Department of Transportation, was designed to study the effect of an SST fleet on the ozone and climate.[66] CIAP was funded at $24 million and lasted three years, with a final report released in 1975. The study predicted that 100 "large" SSTs flying at an altitude of 20 km (about 65,000 feet) would cause a 0.88 percent decrease in global ozone levels over the life of the fleet.[67] A concurrent study by the National Academy of Sciences' (NAS) Climatic Impact Committee predicted that 100 Concordes cruising at an altitude of 16.5 km (about 53,000 feet) for 5 hours/day would cause an ozone decrease of 0.70 percent over the fleet's life. Aircraft flying at altitudes up to about 25 km (80,000 feet), with similar exhaust characteristics, would be expected to induce relatively more serious changes in atmospheric ozone.[68] A year before the CIAP and NAS studies were released, another group of scientists reached roughly the same con-

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[65] NASA Reference Publication, Present State of Knowledge of the Upper Atmosphere 1988: An Assessment Report, Aug. 1988, NASA, Washington, D.C.

[66] Advanced Study Program and the Upper Atmosphere Project and National Center for Atmospheric Research, The Stratosphere and Mesosphere: Dynamics, Physics and Chemistry (Boulder, CO: NCAR, 1975), iii.

[67] Poppoff, I. G., R. C. Whitten, R. P. Turco, and L. A. Capone, An Assessment of the Effect of Supersonic Aircraft Operations on the Stratospheric Ozone Content, NASA RP-1026 (Washington, DC: NASA, 1978), 1.

[68] National Academy of Sciences, Environmental Impact of Stratospheric Flight: Biological and Climatic Effects of Aircraft Emissions in the Stratosphere (Washington, DC: NAS, 1975), 17.

clusions. All these studies predicted that a fleet of HSCTs would cause a decrease in the stratospheric ozone.[69]

In response to the predictions made under CIAP and the NAS report, the High Altitude Pollution Program (HAPP) was initiated by the Federal Aviation Administration in 1976. It ran until 1982. The HAPP study reported that from about 15 to 20 km (roughly 50,000 - 65,000 feet) above Earth, NO_x can catalytically destroy ozone, while at altitudes below 13 km, NO_x emissions are expected to increase the ozone level.

The HAPP report concluded that "there is no immediacy of concern with regard to ozone and climatic changes that may result from the operations of civilian aircraft." [70] This conclusion is based on the assumption that NO_x injections occur primarily at altitudes below 13 km, as would be the case for subsonic, but not supersonic, aircraft. Thus, for subsonic aircraft, the increase in ozone at lower altitudes more than offsets the much smaller decreases in ozone at the higher altitudes, resulting in a net increase in total ozone, according to the HAPP findings. The HAPP study does not state conclusions about aircraft cruising at altitudes above 13 km, as would be the case for an HSCT.

From FY 1973 to FY 1982, NASA funded research on the impact of emissions on the stratosphere under the Supersonic Cruise Research and Variable-Cycle Engine programs. Conclusions reached under the NASA program were similar to those from the HAPP study. In 1978, a research team at Ames Research Center concluded that "realistic fleet sizes should not cause concern with regard to the depletion of the total ozone overburden." [71] For 100 supersonic aircraft using variable cycle engines, cruising at 17.5 km at a speed of Mach 2.3, the authors predicted that total ozone would increase by 0.11 percent to 0.13 percent. The authors note that the difference between their predictions and those of the CIAP study:

> . . . is due largely to the recognition of potential ozone increases in the lower stratosphere that offset the potential decreases in the upper stratosphere. Hence, although the total ozone overburden appears to be affected only slightly according to assessment models, the *distribution* of ozone with altitude is affected more significantly [emphasis in original].[72]

In a 1981 follow-up assessment, NASA scientists reached comparable conclusions, stating that the preceeding quote is "still appropriate" and that "for a fleet of 250 aircraft, the (overall) change in the ozone column is predicted to be very close to zero." [73] It should be noted that all these results were arrived at prior to the discov-

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[69] McElroy, Michael B., Steven C. Wofsy, Joyce E. Penner and John C. McConnell, Atmospheric Ozone: Possible Impact of Stratospheric Aviation, Journal of the Atmospheric Sciences 31, (1974): 287.

[70] N. Sundararaman, The High Altitude Pollution Program (1976-1982) Report # FAA-EE-84-10 (Washington, DC: Federal Aviation Administration, 1984): 31.

[71] Poppoff, et al., 1.

[72] Ibid., 1.

[73] Whitten, R. C., W. J. Borucki, I. G. Poppoff, L. Glatt, G. F. Widhopf, L. A. Capone, and C. A. Reigel, Two-Dimensional Model Studies of the Effect of Supersonic Aircraft Operations on the Stratospheric Ozone Content, NASA RP-1064 (Washington, DC: NASA, 1981): 1.

ery of the depletion in the ozone layer. Therefore, such results are probably suspect on empirical grounds.

In 1987, under a NASA contract, Atmospheric and Environmental Research, Inc. (AER) began studies on the effects of an HSCT fleet on the ozone layer. Within the next few months, NASA will continue the studies with two one-year contracts going to AER and to a research team at the University of Oslo. Using two-dimensional (altitude and latitude) models, AER and the Oslo group will examine HSCT technology assuming specific routes and fleet sizes (scenarios will be provided by Boeing and McDonnell Douglas), determine which emission reduction plans would minimize the impact of the fleet, and compare studies of subsonic fleets in the absence of an HSCT fleet. They will also compare these findings with results obtained using available three-dimensional studies. NASA foresees at least two more years of study on the effects of an HSCT fleet on the ozone layer. NASA has formed an oversight committee to make recommendations for the studies, raise issues to be further examined and provide final approval of the results. NASA spent about $200,000 to $300,000 in FY 1988 studying the effects of supersonic aircraft on the ozone.

NASA conducts an ongoing atmospheric ozone research program which reports to Congress on a biennial basis.[74] Researchers working on ozone as it relates to the HSCT are included in this program at NASA Headquarters and, according to NASA, will be prepared to integrate findings from the larger program into the HSCT program.

SONIC BOOM

Technical Aspects

An aircraft moving faster than the speed of sound creates pressure waves in the atmosphere that grow into shock waves, one leading and one trailing. Shock waves moving downward reach the earth's surface resulting in a sudden increase in atmospheric pressure over ambient levels. The sudden overpressure is heard by the ear as a bang, or sonic boom, and it is usually measured in pounds per square foot (psf). After the increase, the pressure drops below its ordinary level and reaches an underpressure that is typically of the same magnitude as the overpressure. Different sonic boom levels with equivalent overpressures, however, can be accompanied by significantly different underpressures. Finally, as the trailing shock wave passes, the pressure returns to normal. The waveform, or "signature", of the sonic boom's pressure as it increases, decreases and then returns to the ordinary pressure appears as a stretched out "N" and is often called an N-wave.

Most of the tests conducted in the 1960s and 1970s focused on the peak overpressure of the sonic boom. Despite the emphasis on peak overpressures, other characteristics of the wave signature, such as the time to reach peak pressure, may be as important in understanding and minimizing the effects of sonic boom. One characteris-

[74] See, for example, Present State of Knowledge of the Upper Atmospher 1988: An Assessment Report. NASA Reference Publication 1208, National Aeronautics and Space Administration, Washington, D.C., Aug. 1988.

tic may relate to structural damage while another relates to public annoyance. There appears to be no consensus on which sonic boom characteristics correlate best with the level of public acceptance.

Sonic booms occur when an aircraft accelerates from subsonic into supersonic speeds. They also occur continuously during supersonic cruise flight. During cruise, the trail of sonic booms resulting from the aircraft is known as a "boom carpet." Sonic booms due to acceleration are greater than those during cruise because the pressure wave is focussed by acceleration and because the transition to supersonic flight occurs below cruise altitudes. The ground area affected by an acceleration boom, however, is considerably smaller and that boom may be more controllable.

As the following table indicates, overpressures are a function of the speed, vehicle design and cruise altitude of the aircraft. Generally, the intensity of sonic booms experienced at ground level increases with increasing speed and decreases with increasing altitude.

EXAMPLES OF PRIMARY SONIC BOOM INTENSITIES [75]

Vehicle	Speed (Mach)	Altitude (ft)	Overpressure (psf)
Shuttle orbiter	1.5	62,000	2.4
Shuttle orbiter	6.0	128,000	0.7
Concorde	2.0	52,000	1.9
SR–71	3.0	80,000	0.9

Secondary sonic booms are caused either by shock waves traveling upward, reflecting off the atmosphere and returning to the ground, or by waves moving downward, reflecting off the water, to regions of the upper atmosphere where the temperature begins to increase, and then returning to the ground. The majority of shock waves moving upward are not reflected to any extent, and of those strongly reflected, only a small fraction reach the earth. Reflection is largely determined by meteorological conditions, especially air currents.

Due to the distance traveled by the wave, secondary booms are weaker than primary sonic booms and they sound like "muffled 'thumps' or low-frequency 'rumbles.'" [76] The secondary boom carpet can extend by 50 to 200 miles beyond the primary carpet.[77]

Representatives from industry, government and academia convened in January 1988 at NASA Langley Research Center to discuss the state of sonic boom research. Participants concluded that sonic boom theory is well understood for speeds lower than Mach 3, but that research is needed at higher speeds since the theory in that regime is not well developed. The atmosphere is known to affect the shape of sound waves, either sharpening or rounding them, but scientists do not know how well we need to understand

[75] Transportation Research Board, National Research Council, Outlook for Supersonic and Hypersonic Transportation Aircraft, Transportation Research Circular 333, June 1988.

[76] Edward J. Rickley and Allan D. Pierce, Detection and Assessment of Secondary Sonic Booms in New England, Report No. FAA-AEE-80-22 (Washington, DC: Department of Transportation, 1980).

[77] Ibid, 4.

the atmosphere in order to predict sonic booms accurately. A greater understanding of the atmosphere would also strengthen secondary sonic boom theory.

Public Acceptance

Aircraft can be designed now with reduced sonic boom overpressures, but most of these configurations also would have reduced performance. Further, currently achievable overpressures may not be sufficient to reduce the sonic boom to an acceptable level. Some experts believe it is worth pursuing an aircraft that can produce an overpressure less than 1.0 psf, while others argue that the money would be better spent on improving subsonic performance to produce an economically competitive plane that could fly subsonically over land and supersonically over water.

In the United States, most of the data about public acceptance of sonic booms was compiled from studies conducted in St. Louis (1961–1962), Oklahoma City (1964), Chicago (1965), and a series of tests at Edwards Air Force Base in California (1966).[78] The Oklahoma City tests were by far the most extensive, with residents being subjected to 1253 overflights producing sonic booms. St. Louis and Chicago residents were subjected to 150 and 49 overflights, respectively. During the first twelve weeks of the Oklahoma City tests, sonic boom intensities ranged from 1.0 to 1.5 psf. During the last fourteen months, the overpressures were increased to 1.5 to 2.0 psf.

Although both the Oklahoma City overflights and a subsequent opinion survey immediately became controversial, one of the most significant findings was that 73 percent of those interviewed said they could tolerate up to eight sonic booms per day. Some critics of the overflight tests argued that the tolerance level would have been much lower had the sonic booms not occurred at regularly scheduled times and had they occurred at night as well as during the day. In addition, the FAA, the contracting agency, admitted to these flaws in the Oklahoma City tests.[79]

At Edwards Air Force Base, the local population was subjected to eight sonic booms per day with a median peak of 1.69 psf. Citizens exposed to the booms were asked to compare the noise to that of subsonic aircraft, typically measured in perceived noise decibels (PNdB). A power lawn mower, as heard by the operator, is roughly equivalent to 100 PNdB, and a hard rock band is about 120 PNdB. Participants in the Edwards study judged the 1.69 psf sonic booms to have the same level of acceptability as subsonic jet noise of between 105 and 110 PNdB. These results were so discouraging that participants in a meeting of the Office of Science and Technology Coordinating Committee promptly concluded that the SST would never fly over land.[80] It is important to note, however, that no tests were made with sonic boom overpressures at 1.0 psf or less. Whether booms at that level are acceptable and whether it is possible to develop an economic HSCT which produces booms below 1 psf, remains to be determined.

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[78] The information about sonic boom tests during the 1960's comes from Mel Horwitch, Clipped Wings: The American SST Conflict (Cambridge, MA: MIT Press, 1982), 75–77, 78–79, 139–157.

[79] Ibid., 76.

[80] Ibid., 148

A French survey conducted in 1976 provided some evidence that people may become habituated to the sonic boom.[81] The survey reported the following data:

Monthly exposure to sonic booms	0–10	11–30	31–60	61–90	90+
Annoyance (%)	13	25	36	30	23

Although the percentage reporting annoyance decreased with boom frequency above the 60 per month level, the fraction annoyed is still significant, and such numbers may be unacceptable.

There is no convincing evidence to prove or disprove that the force of sonic booms causes physical harm to humans and animals. The boom does, however, cause fear, irritation and startle. Startle is identified as the "immediate involuntary response of a person suddenly disturbed by noise or movement; and that person's immediate retrospective feeling of alarm or distraction." [82] Startle may result in persons injuring themselves or others and in accidents, such as startled horses throwing their riders. Throughout a series of flight tests of the Concorde in Britain, hospital staff were asked to report if their patients were affected by sonic booms; no adverse effects were reported. Studies on animals show slight disruptions in their activities, but generally no more so than when a truck drives by or a subsonic aircraft flies overhead.[83]

Physical Damage Aspects

Property damage from sonic booms generally has been restricted to brittle secondary structures, such as window glass and plaster, although an extreme boom—not likely from an HSCT—could cause structural damage in a weak structure.[84]

Between 1956 and 1970, the U.S. Air Force paid over $1.7 million to settle 37 percent of the approximately 42,000 damage complaints made by citizens living in areas subjected to sonic booms from military aircraft. Half of the claims were for broken glass and 45 percent were for fallen plaster and broken bric-a-brac. Investigations by engineers indicated that, on average, one sonic boom caused one valid damage claim per 300,000 exposed houses.[85]

Legal Aspects

The United States currently prohibits supersonic flights by civil aircraft over land. It also prohibits landing or departure of aircraft that cause sonic booms to reach the United States from international airspace (14 CFR 91.55). In 1980, the Department of Transportation verified that rumbles heard in New England were sec-

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[81] J. Bremond, "Reaction of the French Population to the Supersonic Bang," NASA TM-75487, trans. by Leo Kanner Associates (Redwood, CA) from "Reaction des populations francaises au bang supersonique," Revue de Medecine Aeronautique et Spatiele, No. 51, 1974, 208–218, v. 13.

[82] C. G. Rice and D. N. May, Startle Due to Sonic Boom: Statement of the Problem, Southampton England University, Institute of Sound and Vibration Research Technical Report, Nov. 1969, 1.

[83] Ibid.

[84] U.S. Environmental Protection Agency, The Effects of Sonic Boom and Similar Impulsive Noise on Structures, Doc. No. NTID 300.12 (31 Dec. 1972), 6.

[85] Kamerman, C., L. Sutherland, and Kenneth J. Plotkin, Exploratory Study of the Potential Effects of Exposure to Sonic Boom on Human Health, v. 1: Sonic Boom Environment (El Segundo, CA: Wyle Research, 1986), 2.

ondary sonic booms from the Concorde. Concorde operators voluntarily adjusted their flights to prevent secondary booms from reaching the U.S. territory by dropping to subsonic speed levels earlier in the approach to the U.S. coast. According to DOT's Boston office, there have been no additional complaints of secondary booms.

Nations prohibiting supersonic flight over land include Brazil, Canada, Denmark (including Greenland), West Germany, France, Ireland, Italy, India, the Netherlands, Sweden, and Switzerland. British procedures state that it is the "responsibility of the pilot in command to avoid the production of sonic booms over land." In practice, the Concorde flies along a corridor over the Irish Sea. Saudi Arabia permits supersonic flight only if the plane is landing or taking off in Saudi Arabia. Australia allows overland supersonic flights but only over sparsely populated regions.

AIRPORT NOISE

Aircraft noise standards are set out under Federal Aviation Regulation 36—Noise Standards: Aircraft Type and Airworthiness Certification (FAR 36). Subsonic aircraft are divided into three stages depending on noise level, with Stage 3 designating the quietest airplanes. Aircraft must meet specific noise levels depending on engine type and date of application for certification. Since November 5, 1975, subsonic turbojet powered aircraft applying for certification must meet Stage 3 requirements.

Noise levels, measured at takeoff, sideline and approach points, are adjusted for total aircraft weight and, under Stage 3-takeoff noise, for the number of engines. For example, a plane with four engines, weighing 870,000 lbs or more is limited to 104 Effective Perceived Noise Decibels (EPNdB) [86] for takeoff, 103 EPNdB for sideline, and 105 EPNdB for approach. Tradeoffs can be made, whereby one limit may be exceeded in exchange for an equivalent reduction at another required measuring point. The sum of the exceedances cannot be greater than three EPNdB and no one exceedance can be greater than two EPNdB.

Controlling aircraft noise places a major constraint on airport capacity.[87] While the Federal Government sets noise standards for the design and operation of aircraft, there are no Federal standards for airport noise, and local governments may set stricter limits than those in FAR-36. As traffic continues to grow (a 50 percent increase in takeoffs and landings at U.S. airports is predicted by the turn of the century), noise problems will be exacerbated. Some communities are experimenting with noise budgets, under plans that limit airport noise generation to predetermined daily decibel totals.[88]

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[86] PNdB measurements are described under the sonic boom section of this report. Effective PNdB corrects for discrete tones, such as the whine from an aircraft landing, and for the duration of the sound. EPNdB is the international standard for measuring aircraft engine noise.

[87] This paragraph on airport noise is derived from a May 1988 background paper prepared for the Congressional Research Service by Kevin Dopart and Leonard Wojcik, analysts for the Office of Technology Assessment, Washington, DC.

[88] The budgets are in the form of noise effectiveness forecast (NEF) totals, which are equal to the product of EPNdB and number of occurrences. Under these plans, an airport would be allot-

Continued

Major Issues, Findings and Uncertainties

GENERAL

The three environmental problems discussed in this chapter are all significant and challenging. Substantial research and operational experience must be carried out to determine whether, and how, each should be addressed. In addition, however, each of them incorporates a substantial degree of public response and consequent uncertainties about the acceptability of any technical solution. HSCT program managers must remain alert to these issues and such concerns to ensure that environmental issues are being adequately addressed, both substantively and in the perception of the public as well as foreign observers.

The technology needed to solve each environmental problem may worsen another problem or render an aircraft uneconomic. As an example, for the last several years, designers have been working to produce more efficient engines. In the process, however, they designed engines that burn fuel at higher temperatures and thus produce more ozone-damaging NO_x than earlier models. Thus, solving environmental problems while building an efficient aircraft will require substantial research. And, one must keep in mind that the success of such research is not guaranteed. The possibility remains that an acceptable HSCT cannot be built.

As far as possible, a stable, well-defined set of environmental regulations would be of considerable help to airframe and engine designers and give direction to a research and technology (R&T) program. There are two problems, however, with meeting this objective. First, policymakers can always revise regulations in the light of new scientific understanding. Second, environmental issues are not strictly technical but have a strong political and international component. Therefore, it is unlikely that there can be a strictly technical fix. Despite these complications, at a minimum, some environmental "ground rules" are needed for the R&T program.

OZONE

Of the three environmental issues of concern, ozone depletion is generally considered the most critical. The ozone layer is currently in decline because it is not expected to recuperate from current depletion by CFCs as fast as further depletion occurs due to CFCs already in the environment. Ozone experts predict it will take 100 to 200 years for the atmosphere to repair itself even if all CFC use is banned. Thus, the introduction of a new pollutant may not be tolerated by the public.

Some believe that there is a high probability that an engine with virtually no NO_x emissions must be and, indeed, can be developed. Because of the cost of doing so, however, most industry experts call for an early decision about what level of $N0_x$ emissions will be acceptable. Others believe that the best course is to develop a Mach 4 or Mach 5 plane fueled by liquid methane and using ramjet propul-

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ted a total NEF which the operator could divide up according to his or her priorities, i.e. the airport could accept a lot of relatively quiet planes or a few very noisy planes, so long as the total NEF fell within the allotted budget.

sion, which would produce lower levels of NO_x Still others have suggested that the problem can be solved by flying at very high altitudes where there is virtually no ozone.

There is some confusion about what the use of liquid hydrogen accomplishes in terms of preserving the ozone layer. Since NO_x production is the result of combustion in the presence of atmospheric nitrogen at high temperatures, regardless of the fuel, the ozone layer could be affected even if a so-called clean fuel, such as liquid hydrogen, were used. Engine temperatures, pressures and fuel residence times are critical factors in NO_x emissions for any fuel. What is critical is the temperature at which the fuel burns, not the fuel itself.

Similarly, scientists have disputed the contention that flying at very high altitudes would solve the problem. They claim that an aircraft would have to fly at altitudes above about 160,000 feet (compared to 30,000–40,000 feet for subsonics) in order to preclude ozone damage. Even if NO_x were deposited at high altitudes, however, downward transport of NO_x can eventually reach and deplete the ozone layer. Those who have suggested flying above the stratospheric ozone are typically considering flying at about 100,000 feet which is not high enough to avoid damaging the ozone layer.

Some researchers are concerned that NASA may not be devoting enough research funds to the ozone problem. For FY 1988, NASA spent $200,000 to $300,000 studying the effects of supersonic aircraft emissions on ozone. In the view of the Agency, scientists working on the specific question of emissions cannot, at this stage, absorb more money than is already allocated. In addition, NASA estimates that in FY88 it spent $30 million studying the upper atmosphere in general, with particular emphasis on ozone trends.

There is a consensus that studies conducted on the effects of HSCT emissions should be highly visible and closely coordinated with ongoing research in other sections of NASA and in other agencies, such as the National Oceanic and Atmospheric Administration (NOAA).

If, because of ozone depletion, the United States decided against proceeding with the HSCT, the Government may wish to urge other nations to cancel their programs, or prohibit, for example, other nation's civilian supersonic aircraft from landing on American soil. The success of such a policy would depend on the ability of other countries to operate an economically competitive HSCT fleet without the U.S. market. While the United States is now a focal point of international travel, it is conceivable that a market centered around the Pacific Basin and excluding the United States would be large enough to support a supersonic fleet. Extensive international cooperation in ozone research and protection, however, would make it difficult for another nation to proceed with the HSCT if it were presented with the same data that dissuaded the United States from building its own fleet.

SONIC BOOM

The United States has two main options for dealing with the sonic boom problem: it can attempt to design an aircraft with an acceptable sonic boom level, or it can continue to prohibit civil su-

personic flights over land and territorial seas. While a dual capability plane—flying subsonically over land and supersonically over water—is technically feasible, it would be more expensive to build and operate, and, according to some industry representatives, it would not be economically competitive with subsonic aircraft.

The lack of public opinion surveys on sonic boom, however, makes it difficult to determine what is acceptable. According to some sonic boom experts, there are data from the 1960s tests which could be useful, but have not been analyzed. The SST program managers were interested in community response to overpressures of 1.0 psf and above. For this reason, they did not utilize the data gathered about populations exposed to the lower overpressures, which occurred at the edges of the sonic boom carpet. Analysis of these data might provide insight into public acceptability of lower overpressures.

While there is agreement that sonic booms must be less than 1.0 psf to be acceptable, there remains disagreement on just how much below. In 1988, Boeing suggested that an overpressure level of 0.50 to 0.75 psf might be acceptable. McDonnell Douglas suggested that the initial target should be 1.0 psf or less. Others, based on the Concorde experience, have said the maximum may be as low as 0.30 psf. There is general agreement, however, that current aircraft configurations cannot reach even the 1.0 psf target. The difficulties in establishing a criterion for public acceptability of sonic booms as well as the technical uncertainties in achieving any target, lead some experts to the conclusion that research money is better spent improving the overall efficiency of a plane which flies at both subsonic and supersonic speeds than in reducing the sonic boom.

Some experts argue, however, that if the HSCT cannot fly supersonically over land, it will not be economically viable for two reasons: inefficiency and loss of key markets. The first point is that it will be difficult to build a plane that burns fuel efficiently at both subsonic and supersonic speeds. The second point is that some key routes require substantial overland flight, the New York to Tokyo route, for example, lies 80 percent over land. If an HSCT costs three to four times an equivalent subsonic airplane, flying an HSCT subsonically for great distances would be a poor use of the investment.

Supersonic aircraft routes may be restricted by laws governing the airspace of other nations, thereby reducing the number of routes which an HSCT would be allowed to fly. While there are no international agreements, many Western countries have banned civilian supersonic overland flights. If, with advanced design configurations, airframe manufacturers are able to significantly reduce sonic boom intensity, the U.S. Government would need to determine what overpressures are acceptable to the public and test aircraft that are purported to meet the requirements. International acceptance is vital.

AIRPORT NOISE

Currently available HSCT engine designs cannot meet Stage 3 aircraft restrictions. Furthermore, by the time an HSCT is flying, ground noise limits may be even more restrictive. Some argue that

the HSCT should not be noisier than the subsonic aircraft that will be operating at the same time period. While no one rules out achieving these low noise levels, doing so is considered a severe technical challenge. As with the other environmental concerns, it would be desirable to have static standards which would best match industry and public concerns. Yet, it is recognized that this is very difficult because individual communities have the authority to set their own noise restrictions.

The particular flight characteristics of the HSCT may produce a lower noise output when integrated over the entire area affected by the noise (called the noise footprint) than subsonic aircraft that meet Stage 3 standards even though the peak noise levels may exceed Stage 3 limits. The HSCT will depart and land more quickly, affecting considerably less of the community than other jets. Indeed, the footprint of a Mach 5 HSCT would be smaller than that of current subsonic jets having equal peak noise levels. The HSCT noise footprint can be altered to decrease either sideline or takeoff noise, although one is usually reduced at the expense of increasing the other. This tradeoff offers more flexibility in dealing with noise, and it may make sense for the FAA to alter the way aircraft noise is measured. Specifically, a Stage 4 limit might measure the overall footprint rather than measuring noise at the distinct points of takeoff, sideline and approach, or it might adjust restrictions to allow for more flexible tradeoffs of EPNdB levels among the three measuring points. Public acceptance would be crucial to any variations in monitoring airport noise.

MARKET ASPECTS

CURRENT ESTIMATES OF THE MARKET FOR HSCT

INTRODUCTION

The ultimate success of an HSCT would depend on whether it can meet a recognized market of sufficient size and do so at acceptable levels of price, performance, reliability and safety. Each of the aspects of the marketability of an HSCT is uncertain at present, and, to some degree, will remain uncertain until substantially more effort has gone into a R&T program to determine the cost and operating parameters of a realistic design.

The market economics of an HSCT are likely to be heavily influenced by governmental participation, incentives and other interventions in the United States and abroad. For example, while the Concorde is currently profitable, this is so only because the British and French governments absorbed much of the up-front cost of development, as well as part of the costs of purchasing the existing fleet. As noted below, various proposals have been made for Federal subsidy of an HSCT, ranging from cost sharing in R&D, to funding an initial commercial prototype, to tax incentives for purchase of the entire fleet. Therefore, projections of the economic viability of an HCST depend not only on market and technology forecasts, but on projections of government policy as well.

There are two other sources of major uncertainty in HSCT economics. One lies in the future costs of fuels, both for the HSCT and for competing subsonics, which may or may not use the same fuels. The other uncertainty arises from the uncertain projections of the future economics of the next generation of subsonic aircraft with which an HSCT would have to compete.

In the presence of so much uncertainty, the only available analytic approach to assessing the marketability of an HSCT is to model the economics based on a consistent and reasonable set of assumptions. NASA has begun to support such work under the current contracts. In October 1986, Boeing and McDonnell Douglas, under contract to NASA, began a three-phase, two-year study on the High Speed Civil Transport (HSCT). Under all three phases, the companies were requested to perform a first order market study of the HSCT. The results of the Phase II studies were released in February 1988.[89]

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[89] The information on the Boeing and McDonnell Douglas Phase II studies is derived from viewgraphs presented to the Congressional Research Service via NASA. In addition, representatives of Boeing, McDonnell Douglas and Langley Research Center provided further explanations of the assumptions and results of the studies.

ASSUMPTIONS

Boeing assumed that an HSCT fleet would not serve routes shorter than 4500 km. McDonnell Douglas chose a slightly shorter distance of 3600 km. Boeing further assumed that there would be no supersonic flights over land and excluded intraregional routes such as New York to Los Angeles and London to Rome. While McDonnell Douglas allowed for supersonic overland flights, it also excluded intraregional flights. Both companies excluded routes with low passenger demands.

Boeing and McDonnell Douglas agree that there will be an increase in demand due to savings of flight time (especially between the United States and the Pacific Basin), but neither included market stimulation in the projections because of a conservative approach and a wide range of possibilities. Finally, both companies assumed that current airports must be used, and that turnaround time would be two hours based on current airport scheduling practice. A one and one-half hour turnaround, which may be achievable, would improve the economics significantly.

TRAFFIC AND FLEET PREDICTIONS

Using the above assumptions, Boeing and McDonnell Douglas projected the levels of international traffic that would be served by the HSCT in 2000. Projections were derived by totaling the air traffic between pairs of cities meeting the criteria listed above. Boeing predicted 315,000 passengers per day while McDonnell Douglas predicted 193,000. According to company representatives, the differences in projected traffic levels are not considered significant since there was no attempt to perform an exhaustive market study.

Assuming a 247 passenger aircraft operating at speeds ranging from Mach 2.4 to 4.5 and with a range of 9000 km, Boeing suggests that between 700 and 750 aircraft (depending on the cruising speed) would be needed to serve the market in the year 2000. McDonnell Douglas projects that with a 300 seat aircraft, a 10,500 km range, operating at Mach 2.2 to 5.0, and a one-hour turn-around time, between 240 and 370 planes (depending on the speed) would be required to serve the market in 2000. By 2025, McDonnell Douglas suggests that the fleet requirement could grow to between 1,250 and 1,940 aircraft.

COMMERCIAL VIABILITY

Despite the recognition of significant market opportunities, neither company was able to demonstrate commercial viability for an HSCT based on assumed technology levels. Boeing found that airline and manufacturer targets for return on investment could not be achieved at yields (gross revenues per seat mile) equivalent to what the airlines have today. Similarly, McDonnell Douglas found that without fare premiums, the HSCT would not be viable.

AIRCRAFT SPEED

Under the NASA contracts, Boeing and McDonnell Douglas were asked to study aircraft within the speed range of Mach 2 to 5. Based on its Phase II examinations, Boeing concludes that the

market is more attractive for an aircraft flying at Mach 2.2 to 3.2. Flying at Mach 3, a 7500 mile trip (e.g., Los Angeles to Sydney) would take about four hours. Scheduled time for existing subsonic aircraft for the same trip is 14.5 hours. During Phase III of the study, Boeing will not consider a Mach 5.0 version.

McDonnell Douglas, on the other hand, concluded that speeds greater than Mach 3.0 would produce greater potential aircraft productivity, and will consider only these higher speeds during Phase III analyses.

Major Issues, Findings and Uncertainties

CUSTOMERS AND TICKET FARES

There is a general consensus that a fare premium would be needed in order to make the HSCT economically viable. Increases over subsonic plane ticket prices would probably vary depending on seating class. For example, tickets for coach might be 15 percent higher, business 25–30 percent higher, and first-class 50–75 percent higher. At these fares, it is believed that the HSCT could capture most of the market currently forecast for those routes identified in the Boeing and McDonnell Douglas studies.

If, on the other hand, all fares were increased 50–75 percent, the HSCT would likely serve only business and first-class, as is now the case with the Concorde, because coach and discount coach passengers are very sensitive to fare levels. While some believe that the business and first-class markets are large enough to sustain an HSCT fleet, most are convinced that the HSCT must serve all three market classes. Furthermore, the HSCT likely will be less attractive politically if it is seen as transportation only for the elite and as not serving the majority of the traveling public.

There is some concern that making the assumption that HSCT ticket prices can be increased to make up for any shortfall in HSCT economic value, may lead to short-sighted technology goals. According to this view, it is better to try to develop an aircraft that is economic without a fare premium, than it is to assume a premium since unforeseen developments may ultimately drive up the cost of any aircraft.

MARKET EFFECTS OF SUBSONIC FLEET

Recently there has been concern that the current subsonic fleet may be aging more rapidly than previously assumed, requiring more rapid fleet replacement. This raises the question of whether airlines will be in the market for a supersonic transport by the time the HSCT could become available. According to some airline companies, a new buy of subsonic aircraft would delay their needs for an HSCT. Others have argued that the first production run for HSCTs will be small enough that initial purchasers will not be influenced by other aircraft purchase requirements.

Regardless of when supersonic aircraft enter the market, subsonics will continue to play a significant role in international travel. Market penetration by an HSCT would be slowed by the presence of depreciated subsonic planes that have low marginal costs of operation. Airframe companies may need to recoup their investments

in subsonic aircraft production before investing heavily in a supersonic aircraft. On the other hand, the production of an HSCT could be used as a wedge for a foreign aircraft manufacturer to enter the commercial airplane market. In this case, producers in the United States might have no choice but to retire their investments in competing portions of their subsonic fleet sooner than they would prefer.

Once HSCTs have a significant presence in the total fleet, they would influence the economics of the subsonic fleet. Typically full fare flyers subsidize discount flyers. If all the first-class and business passengers were to fly on a premium fare based HSCT, the economics of the subsonic planes, on parallel routes, would be degraded, probably requiring fare increases that could further erode the subsonic market.

MARKET ACCESS

It has been suggested that the United States may have to enter into an international consortium for HSCT production in order to gain access to the markets of other countries. There is some concern that foreign governments might prohibit supersonics from landing on their territory unless they or their companies are partners in production. At this time, no such indications have emerged. In addition, an international consortium could give added incentive to reach agreements on international environmental standards and aircraft certification. Any international production arrangement should be assessed to determine the value to the United States in terms of market share and balance of trade.

SUPERSONIC OVERLAND FLIGHT

There remains disagreement about whether allowing supersonic flight only over water would preclude an economically competitive HSCT. While most believe that such a policy would impede but not prevent such an aircraft, some have argued that important routes (such as New York to Tokyo) could not be economically served unless the aircraft can fly supersonically over land as well as over water. Almost 80 percent of that route is over land. These analysts further claim that without such routes, an HSCT fleet would not be able to compete with advanced subsonic aircraft.

ADDITIONAL MARKET STUDIES

There is a consensus that more thorough market studies must be conducted before proceeding with HSCT production. Furthermore, a series of economic studies done independently of NASA might be essential if sound decisions about the rate and direction of a research and technology development program are to be made. These studies should include development of a methodology and involve extensive sensitivity analyses to assess the effects of changing market conditions and environmental requirements. Development, production and operational costs, including those for possible upgrading of the air traffic control system and air system infrastructure, should be included in economic calculations. In these studies, any comparisons between supersonics and subsonics should be

made between equivalent planes; i.e., comparison of an HSCT to the advanced subsonic aircraft expected at the time the first HSCTs will enter the market. Because of the many uncertainties, however, considerable care must be taken in designing such studies, and their assumptions, methodologies and results should be carefully documented and made available to analysts for public evaluation.

AIR TRANSPORT SYSTEM [90]

Introduction

Technology development, environmental effects, and market economics will determine the feasibility of an HSCT. Less critical, but also important, is an HSCT fleet that will fit into the civil aviation system in the United States and worldwide. HSCT development and operations will affect and be affected by airport operations, air traffic control, certification and regulation.

Airport Operations

There are over 16,000 airports in the United States of which approximately 550 are available for commercial aircraft. Commercial air traffic is highly concentrated with 72 airports accounting for some 90 percent of passenger traffic. Most commercial airports are publicly owned and operated by either local governments or public authorities.[91]

Limits on commercial airport capacity will impede new air transportation services, and currently planned technological developments will solve few of these problems. Economics and regional politics, and perhaps international politics, will play major roles in solving the problems of limited capacity. Local governments and interests have successfully blocked much airport expansion, with aircraft noise usually at the center of the campaign.

Congestion and delay will affect all major airports for the foreseeable future. Currently, airport demand is managed through air traffic flow control, slot restrictions at four airports, and government/industry scheduling meetings when problems occur or are anticipated. Congestion mostly occurs during relatively short peak demand times, and most delays result from poor weather conditions that limit airport capacity. As demand grows, the peak times may become longer.

For aircraft in international service, U.S. Customs Service procedures, as well as those of other nations, can affect the time an arriving vehicle must spend undergoing post-arrival search and other procedures. Essentially, the airlines must suspend all maintenance, loading and unloading, catering, refueling, and other operations while they are undergoing search. And, depending on the design and the operational rules in place, some airports may require aircraft in international service to arrive and depart from different

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[90] The description of the air transport system is derived from a May 1988 background paper prepared for the Congressional Research Service by Kevin Dopart and Leonard Wojcik, of the Office of Technology Assessment, U.S. Congress. For an extensive discussion of the current air transport system see U.S. Congress, Office of Technology Assessment, Safe Skies for Tomorrow: Aviation Safety in a Competitive Environment , OTA-SET-381, Washington, D.C., July 1988.

[91] Apogee Research, The Nation's Public Works: Report on Airports and Airways (Washington, DC: National Council on Public Works Improvement) 1987, 4-5.

gates or terminals, which can add to the time required for completion of turn around. In addition, some passengers and/or freight arrive in the United States only while in transit between two or more other countries, and they too may have to undergo certain customs procedures that can add to their total travel time.

Early involvement of customs authorities in the design and planning for HSCT operation might help anticipate and plan for any changes in procedures or in aircraft technologies that could speed the passage of aircraft through customs and on into operational ground servicing. Suggestions have been made by customs authorities in the U.S. that designers limit the number and size of separately-accessible compartments on aircraft to speed search procedures, that systems be included on-board that would allow authorities to determine whether compartments were opened by unauthorized personnel during flight or ground operations, or that provisions be made in aircraft design to facilitate the flow of air throughout its many compartments to reduce the time needed to check for hidden contraband such as narcotics using dogs or chemical detectors.[92] These kinds of changes might require compromises with other aspects of aircraft design, safety, and operations, however, and should be evaluated in the light of possible degradation of other important characteristics, including weight.

Air Traffic Control

The terminal area control aspect of air traffic control is performed by Terminal Radar Control (TRACON) facilities, which control traffic within 30 miles or so of airports, and airport tower cabs, which control traffic within about 5 miles of the centers of airports. Positions of aircraft over land are monitored by surveillance radars and the information is displayed to air traffic controllers. Controllers communicate with pilots over radio.

Nine facilities in the United States control enroute air traffic over segments of the Atlantic and Pacific Oceans. Since surveillance radars do not provide coverage over vast portions of the Atlantic and Pacific Oceans, pilots transmit position information from on-board instruments to controllers over high-frequency (HF) radio, typically every 45 minutes to an hour. HF radio communications are not always reliable, however, and aircraft navigation systems may have substantial inaccuracies. Thus, oceanic standards for safe separation distance between aircraft are large compared to standards over land, where there is radar coverage.

Several major developments are expected in air traffic control by the early 21st century, spurred by increasing traffic levels. Systems for automating air traffic control functions are under development, as are cockpit collision avoidance and traffic display systems. Automated air traffic control should reduce air traffic controller workload and permit more flexible use of airspace, and cockpit collision avoidance and display systems may permit closer safe aircraft separations.

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[92] Samuel Banks, Assistant Commissioner for Inspection, U.S. Customs Service, personal communication, December 28, 1988.

Also under development is automatic dependent surveillance, in which an aircraft sends position information automatically to ground control facilities via satellite data link. This system promises to replace the relatively unreliable HF radio position reporting. The Global Positioning System (GPS) is a satellite system, designed primarily for military use, that would provide accurate 3-dimensional position, velocity and time information. Its use could reduce navigational error (and hence, reported position error) over the ocean from about 5–10 miles to about 100 meters. This improvement could permit closer safe aircraft separations and freer use of oceanic airspace. Control of oceanic airspace is shared by many nations and more international air traffic control coordination can be expected in the future through long-distance communications systems.

Certification and Regulation

The Federal Aviation Administration (FAA) will face a number of developments in subsonic aircraft during the next decade which will pose certification challenges; these include propane engines, automated cockpits, tiltrator aircraft and fly-by-wire/fly-by-light aircraft control systems. The FAA has traditionally relied upon industry expertise when certificating new aircraft, as commercial developments have often outpaced government technical expertise. Airworthiness standards for transport aircraft are spelled out in the Code of Federal Regulations, under 14 CFR 25.

Crew rest requirements are among the more significant areas for regulatory review. Presently, Federal aviation regulations do not consider the number of time zones crossed in establishing crew rest requirements. However, subsonic aircraft operating with ranges in excess of 12,800 miles during the next decade may stimulate Federal rulemaking in this area.

Major Issues, Findings and Uncertainties

AIRPORT OPERATIONS

It is very desirable that HSCTs be able to operate on existing airport runways, taxiways, and ramps. Some small modifications may be called for in taxiway turning areas, but current design studies show negligible effects of proposed HSCT configurations. They also will very likely have to fit into the hub and spoke system that characterizes the current airport system. HSCTs may also adapt well to the new superhub concept if it comes about.

Fuel costs and availability will be a prime economic factor in airport operations. As discussed in the section on technology there are three candidate fuels for an HSCT depending on speed; Jet-A, JP–7, or cryogenic (liquid methane or liquid hydrogen). If JP–7 or cryogenic fuels are used, new and distinct sets of fuel storage facilities would be required at all HSCT airports. The refrigeration requirements for cryogenic fuels could be particularly costly. Fuel storage facilities are not now politically sensitive, and may not be in the future, unless the new fuel is judged to be much more dangerous to transport and store than conventional fuels.

Cryogenic fuels also present particular safety problems. Because both hydrogen and methane are lighter than air, if there should be a leak of either liquid hydrogen or methane, the vaporization of these fuels upon contact with ambient temperature would create a flammable cloud unlike a leak of Jet-A or JP-7. When in a storage tank, however, neither liquid hydrogen or methane pose any greater safety hazard than Jet A or JP-7. Therefore, the ground facilities for cryogenic fuels would require particularly stringent leak prevention measures, similar to those that would be needed in flight operation. Even so, the presence of cryogenic facilities at airports could elicit public concern similar to that which occurred during the liquefied natural gas siting debates of the 1970s.[93]

It is possible that an HSCT will require special maintenance and inspection facilities at airports. The costs and operational problems associated with such facilities are not presently known but, along with costs for fuel facilities, should be included in market analyses of the HSCT.

AIR TRAFFIC CONTROL

The high operational cost of an HSCT and the emphasis on flight time-savings may mean that an upgrade will be needed in the international Air Traffic Control (ATC) system in order to minimize the turnaround time of the HSCT fleet. The possibility that global satellite navigation and communication systems for air traffic will be in place by the time an HSCT is flying would take care of this upgrade. Some argue that because of its high cost, an HSCT would warrant priority over subsonic aircraft for access to landing slots. Others argue that it is unlikely that the HSCT would be given priority over subsonic aircraft regardless of the condition of the international ATC system. Therefore, any upgrade would benefit subsonic fleets as well.

Some speculate that the presence of a significant HSCT fleet would ease ATC problems by extending the span of cruising altitudes and allowing a more uniform distribution of scheduled departures. Many of the current ATC overload problems occur because aircraft fly at about the same altitude. Thus, by flying at significantly higher altitudes—over 60,000 feet for HSCT versus 30,000–40,000 feet for subsonics—HSCTs may ease enroute traffic congestion. Since flight times would be shorter, scheduling constraints may be eased and air traffic controllers will be better able to predict the weather that HSCTs will encounter during flights and at their destinations.

HSCT operations may require air traffic controllers who specifically control traffic at very high altitudes, depending on the number of HSCT flights. However, air traffic control automation, and collision avoidance and traffic display systems in the cockpit, may reduce or even eliminate the need for air traffic controllers for the enroute portions of oceanic flights. It will be important to avoid holding HSCTs in the air because of their high fuel consumption and large turning radius.

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[93] U.S. Congress. Office of Technology Assessment. Transportation of Liquefied Natural Gas. OTA-O-53. Washington, September 1977.

It is expected that an HSCT would be designed to fly at speeds similar to subsonic aircraft in the terminal control area. However, procedural rules, such as those governing independent use of parallel runways, and collision avoidance alert thresholds, may need to be modified to reflect the possibility that an HSCT may be less maneuverable than a subsonic jet in the terminal area. Some industry analysts argue that an HSCT must be designed to be no less maneuverable in this airspace than any other commercial jet.

CERTIFICATION AND REGULATION

Major changes in design, production, and operating certification policy and procedures may be necessary in view of the technological advances expected for the HSCT. Some have argued that it is critical for the regulatory agencies to be directly involved in an HSCT program even at the early stages of research and technology development. Since the government may well be extensively involved in developing HSCT technologies, it may be possible for the FAA to conduct ongoing evaluations of technologies, thus easing the certification process.

An HSCT would be subject to the airworthiness standards for transport category aircraft, (14 CFR 25) plus additional requirements unique to supersonic aircraft. For example, fail-safe cabin pressurization is not required under 14 CFR 25; however, at the cruise altitudes expected in new generation supersonic aircraft, depressurization would prove fatal to passengers and crew and an HSCT must be designed so that the chances of it happening are acceptably low. Evaluation of the impact of HSCT on jet lag in flight crews would be necessary, taking into account aircraft speed and airline scheduling practices. By reducing the flight time for long-distance routes from 8 to 14 hours to 2 to 4 hours, an HSCT might mitigate jet lag effects now experienced by flight crews on subsonic international flights.

POLICY AND PROGRAMS

First Stage

THE NASA PROPOSAL AND RELATED PROGRAMS

In response to a request by the Senate Commerce, Science and Transportation Committee, NASA has prepared a ten year research and technology program to meet the environmental and economic requirements of a high speed civil transport (HSCT) in the first decade of the next century. The purposes of this program would be to help maintain U.S. leadership in aerospace technology into the 21st century and to ensure that the Nation continues to enjoy a positive trade balance in commercial aircraft. The program would focus on the four most important areas of technology for the HSCT—propulsion, aerodynamics, structures and materials, and systems—with the objective of increasing operating efficiency for an HSCT well above that which could be achieved with current technology. Efficiency increase (lower fuel consumption) goals are set for each technology group.

Although the program is aimed at developing technologies for an HSCT, NASA does not intend to build an aircraft prototype or even prototypes of major components such as a propulsion system. Rather, NASA hopes that at the end of the research and technology program, the technology will be validated to the point where the U.S. aerospace industry will move forward and develop a commercial HSCT. To help ensure this, the program is to be a joint industry-government activity along the lines of previous efforts under the leadership of NASA and its predecessor NACA.

Although NASA has not yet provided cost figures for the program, the most likely estimate from industry at this time is that the entire ten year research and technology program would cost about 1.5 to 2 billion dollars. This would include both NASA and industry contributions. For FY90, the aeronautical research and technology portion of the NASA budget request is about $462 million, so the HSCT research and technology program could represent a substantial increase in funding. Further, there are some experts who feel that the research and technology program may cost considerably more than 1.5 to 2 billion dollars. They reason that the uncertainties in achieving the technical goals of the program and in the availability of research personnel make it very difficult to come up with a good estimate. Indeed, a few argue that a 1.5 to 2 billion dollar cost can be obtained only if the design cruise speed is confined to Mach 2 to 3.5 and the R&T program is carefully integrated into an aircraft development program.

In addition to the research and technology program, two other research areas are of importance for the proposed HSCT program. The first is the effort to examine the Earth's ozone layer. Current-

ly, the United States has mounted a large effort—called the U.S. Global Change Program and involving several agencies, including NASA—to examine the geosphere. One of the major targets of the program is to determine the extent of damage to the ozone layer due to emissions of man made gases. This program will serve as the U.S. contribution to the International Geosphere-Biosphere Program (IGBP) to begin in 1992. One IGBP objective is better understanding of the changes occurring in the earth's atmosphere resulting from human activities.

Since there is considerable concern about the effects on the ozone layer of a fleet of HSCTs, it is important to have a clear understanding about the magnitude of these effects if proper control technologies are to be designed. The fact that NASA is an important participant in global ozone research programs should facilitate information exchange between that research and an HSCT research and technology program.

The importance of close coordination between research efforts and standard setting on ozone protection and aircraft noise is difficult to overstate. Propulsion system technology goals depend critically on these environmental requirements, and the research and technology program eventually must know what these requirements will be. A possible approach is to assume a demanding set at first—e.g., no significant NO_x emissions—and review these goals periodically in light of continuing environmental research. After a few years into the research and technology program, the technical goals could be adjusted, if appropriate, to reflect any changes in what is acceptable for ozone protection and aircraft noise. A similar program could be carried out for sonic booms.

The other related research program is the development of the National Aerospace Plane (NASP). As discussed above, there appears to be little overlap between the technologies that will be developed in the NASP program and those to be covered in an HSCT program confined to speeds below Mach 4. NASA has indicated, however, that some of the NASP work—primarily in materials and computer analysis methods—is applicable to an HSCT. A redirection of the NASP program to lower Mach numbers, however, could greatly increase overlap. Such a change would probably result only if the commercial aspects of NASP were given higher priority than now is the case.

POLICY ISSUES

One of the major uncertainties about the NASA proposal is what constitutes technology validation. As currently defined by NASA, validation means that the technology is proven to the point that industry is willing to move forward with prototype and commercial development if a market appears. The definition lacks precision. The NASA goals of direct fuel consumption reduction appear to be difficult to measure without actually building an aircraft, a step which is not now planned. Indeed, since NASA does not intend to build prototypes of any major components, cost reduction measurement will be even more difficult and will have to be inferred through the attainment of design goals which can be measured explicitly. An important consideration in evaluating the progress of

the NASA program, should it be approved, would be a clear definition of how the technology goals will be measured and what constitutes technology validation in terms of those goals.

An important concern for the stability of an HSCT research and technology program is the competition for funds with the space program within the total NASA budget. While the cost of the HSCT program would be considerably smaller than reasonably expected costs of the space program over the same period, overall Federal budget pressures coupled with unanticipated needs in the space program could threaten an HSCT budget at any time. Indeed, if the space program is to do more than remain in a holding pattern over the next several years, a large increase in the NASA space budget will be necessary.[94] This alone could be enough to keep the HSCT program from getting started. Therefore, a compelling case may have to be made about the economic potential of this aircraft if it is to go forward in the face of stiff competition from the space program. Further, if the HSCT research and technology program is started, continuity will be important if it is to have a chance for success.

An HSCT research and technology program also will have to compete with other aeronautical programs for personnel and equipment. The National Aerospace Plane program will certainly generate such competition, as would other programs such as the subsonic transport and civil tiltrotor/commuter proposals also being made by NASA in response to the Senate Commerce Committee request. Currently, there does not appear to be a major problem with access to such resources as wind tunnels and large computers. More likely is a shortage of skilled personnel (e.g., mechanical designers who are already in short supply) to undertake all of these programs. If such a shortage does come about, the labor costs of the HSCT program may rise sharply.

Currently, the HSCT research and technology program is to be a NASA directed, cooperative effort with industry in the manner of previous programs run by NASA and its predecessor NACA. This organizational arrangement has met with much success over the years, most recently with the Aircraft Energy Efficiency program. As a result, industry believes that this approach is best for the HSCT program. The size and complexity of the proposed HSCT research and technology program, however, is likely to be considerably greater than previous NASA efforts. Therefore, it may be useful to examine alternate organizational arrangements. One possible model is the SEMATECH program to develop new manufacturing technologies for the production of semiconductor chips.[95] SEMATECH is a joint venture of several large semiconductor manufacturers with co-funding from the U.S. Department of Defense. A board of the industrial partners and DoD, with each member having one vote, will direct operations. The reason given for the cooperative effort is that the cost of developing the advanced semiconductor processing technology needed for the United States to

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[94] U.S. Congress. Congressional Budget Office. The NASA Program in the 1990s and Beyond. Washington, D.C., May 1988.

[95] U.S. Library of Congress. Congressional Research Service. Semiconductor Manufacturing Technology Proposal: SEMATECH. Issue Brief No. IB87213. Washington, D.C. (continually updated).

regain world leadership in memory chips is too great to be borne by any one manufacturer.

A similar argument holds for any commercial HSCT. In fact, as will be explored below, development of a commercial HSCT may require an international consortium. An arrangement similar to SEMATECH might be an effective way to carry out the research and technology program. Since there is good reason to go with NASA because of its past record in this area, the best approach may be to begin with its HSCT program with the option of modifying it if necessary. Indeed, if all or most of the R&D funding came from the Federal government, there would be a strong case for a single, focused project in one lead agency, which most appropriately would be NASA.

Follow-on Program

DESCRIPTION

While the research and technology program described above might well successfully develop and validate the key technologies needed for a commercially successful HSCT, the aeronautics industry still might not go ahead with commercial production. There is almost a consensus in the industry that a prototype aircraft will have be built before any commitment to commercial production is made. Some industry analysts estimate the cost of such a prototype to be between 5 and 10 billion dollars, although this is highly uncertain. Before such a prototype is built, however, many feel that the Federal Government would have to support large scale demonstration of propulsion systems and major structural components, a step beyond technology validation. A propulsion demonstrator would probably not require flight testing, however, because of the capabilities of altitude simulation test facilities. There is some feeling from industry that the Federal Government also would have to provide significant support for the construction of the prototype aircraft.

POLICY ISSUES

The costs of developing a commercial HSCT, even with a highly successful research and technology program, will undoubtedly be very high, higher than for any subsonic commercial aircraft. In addition, payback times for new generation subsonic aircraft have been lengthening because of an increasingly competitive air transport industry. For example, the development costs of the Boeing 757, which made its first appearance in 1978, have just now been recovered with the sale of over 160 of these aircraft in 1988 alone. So far, over 400 of these aircraft have been sold since its introduction, whereas sales of about that number were needed to begin making a profit. The result of these financial conditions is a feeling on the part of the aerospace industry that the industry alone will not be able to handle the costs of developing a commercial HSCT following the completion of the research and development program.

While there is consensus in the industry that government assistance of some kind will be needed, there is little agreement about the form of that assistance. Industry representatives feel that the

proper role for NASA is to do the research and technology to resolve the high technological risks, but that the industry should lead development of the program from that point even if additional Federal support is needed. One proposal is for the government to buy the first several aircraft to be produced. This would provide a guaranteed market that could give the industry enough assurance of recovering their investment that they would proceed with commercial development after technology validation and demonstration. A difficulty with this approach, however, is the uncertainty about how many planes would have to be bought in order to provide a sufficient incentive. With the very high development costs and an uncertain market, the number of planes that would need to be purchased may be excessive for any purpose (most likely military transport) that the government may have.

Another concern is that government purchase may lead to over specification or inappropriate specification of the aircraft, which would add substantially to the development costs if the industry had to make significantly different planes for the government and for the commercial market. While raising concerns about specification may be understandable, such concerns may not be justified, particularly if the major purpose of the government purchase is to stimulate domestic production. The Air Force's purchase of the KC-135, which helped get the development of the commercial version, the Boeing 707, off the ground, did not seem to affect the commercial configuration of that aircraft. If the government buy option was pursued, it would be necessary to ensure that government specifications did not add unnecessarily to the ultimate cost of the commercial version of an HSCT.

Some analysts have suggested tax credits, guaranteed loans and other financial assistance to help the industry proceed with commercial development of an HSCT. The potential for these options cannot be determined at this time because of the uncertainty of development costs and the market conditions at the time an aircraft would be available. The likelihood that development costs will be very high, perhaps a large percentage of the industry's worth, however, means that such incentives may not be sufficient by themselves to convince the industry to move ahead. In conjunction with a guaranteed purchase or, as will be discussed, with an international consortium, such financial incentives might be quite helpful.

At this time, most of the industry believes that development of a commercial HSCT will have to be an international effort. The way now favored is an international consortium, led by the United States, building on the technology validated and demonstrated by this country. The principal factors which urge an international approach at the commercial development stage are the very large size of the investment needed to start production and the international imperatives of the environment and air transport system issues. Additionally, a commercial HSCT fleet would require landing rights in several countries.

While it seems probable that the U.S. aerospace industry will not be able to develop a commercial HSCT fleet on its own, the industry and NASA still want the United States to take the lead in developing the technology. This raises the issue of whether an international consortium for aircraft production is possible if the United

States does not also share in the research and technology program. Foreign competitors are currently carrying out exploratory research and development programs on different HSCT concepts. Indeed, one of the principal reasons for advocating a U.S. program is because of concerns that these economic competitors will develop a commercial HSCT if we do not. While only a few industry analysts have called for cooperative efforts at the research end, the possibility that there will be no international partners for production, should they be needed, if there is none at the research end has not been completely dismissed.[96] Such research cooperation may not have to be very extensive and could still easily preserve a U.S. technological lead. But it may be important to explore more thoroughly the consequences—both positive and negative—of going it alone at the research stage before any major funding commitment is made.

Finally, although a prototype is likely to be needed if commercial production is to take place, it is probably now premature to commit to building a prototype. There are many market and environmental uncertainties that must be cleared up before a rational decision about the next stage can be made. There should be, however, flexibility to make those decisions and to rapidly commit to a prototype if the country is to maintain any technology lead it gains through the research and technology program.

Options for Congressional Action

The primary issue for the Congress is whether to authorize a formal program for NASA to develop the research and technology base for a new generation of HSCT. The decision would require a balancing of the uncertain future benefits that would accrue to the Nation if an HSCT can be built and operated successfully against the costs of the program in a time of budget constraint. The benefits include the possibility of major export earnings and job creation while the costs are those of the program itself. The uncertainties in benefits arise from the possibilities that one or more of the environmental constraints cannot be met or that the economics of any resulting aircraft will not be acceptable.

If the Congress chooses to fund the research and technology program proposed by NASA, or a similar program, there are several important considerations that need oversight and analysis as the program unfolds. These considerations, which are derived from the above analysis, fall into two categories. The first is a set of considerations about the direction and effectiveness of the research and technology program. The second is a set of considerations about making decisions on whether and how to proceed with a prototype and eventual commercial development of an HSCT.

In this section, these considerations are presented in the form of actions which the Congress may undertake in its oversight function should the research and technology program be undertaken. The first set of actions would help ensure that (1) the program remained as flexible as possible to accommodate changes in major pa-

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[96] Proposals for Developing High Speed Commercial Flight. Technical memorandum 88-02, Battelle, Columbus, OH, Aug. 1988.

rameters such as environmental restrictions, and (2) the program was constantly aimed at developing technologies that could produce an aircraft acceptable to the public. The second set of actions would be designed to help the Congress make those policy decisions that may be necessary for ultimate development of a commercial aircraft.

PROGRAM OVERSIGHT

The Congress may wish to ensure that the assumptions which would guide the program are clearly understood, visible and agreed to by all program participants. These assumptions include the economic targets the HSCT would have to reach, the environmental restraints it would have to satisfy, the market for these aircraft, and the condition of the air transport system in which it would have to operate. Since these assumptions directly translate into technology goals, the linkage between the two would also have to be spelled out clearly so that the Congress could effectively monitor program progress. In particular, if the program officials were to make changes in any of these assumptions as the program evolves—e.g., allowable aircraft noise levels, or sonic boom prohibitions—it would be important to make the Congress aware of those changes so that technology development would not proceed in directions that might lead to an aircraft unacceptable to the public and, therefore, unable to be flown.

The Congress may wish to have the specific targets to be met by the technologies which NASA would develop and validate clearly identified at the start of any program. Included in this prescription would be a clear description of how progress would be monitored. In other words, if the goal of the program is to achieve efficiency improvements and cost reduction compared to existing technology, it would be important for NASA to tell the Congress just how such improvements can be measured unambiguously, including whether such measurements require prototypes. The Congress also may wish to ask that a decision about the Mach number range to be pursued by the program be made as early as possible. In particular, if the program were to be aimed at developing technologies in the Mach 2 to 5 range, it would be important to know about any added complexity and cost that would accrue due to the different technologies needed for aircraft flying above Mach 3.5 to 4.

The Congress may wish to monitor carefully the interaction between the NASA research and technology program and other relevant environmental research programs, particularly those examining the ozone layer. Congressional guidance could be very important in ensuring that any HSCT program is continually aware of new findings about the environment that could change the requirements for the technologies it is developing. In a related matter, possible restrictions (e.g., fuel taxes, efficiency targets) on fossil fuel combustion due either to environmental concerns or energy security concerns, could significantly affect the direction of NASA research, particularly about propulsion systems, aerodynamics and materials. Congressional oversight to ensure close NASA attention to these possibilities could be important.

In addition, the Congress may wish to require periodic, independent analyses of the market conditions that are likely when the aircraft is to be available. Such analyses could assist the Congress in reviewing the direction and achievements of the NASA program and in evaluating the likelihood that the program would lead to the development of a commercial HSCT. Congress may wish to ask its own analytic agencies to review the economic feasibility from time to time. It may also urge NASA to fund such studies at organizations that do not have major stakes in the outcome.

In a program such as this, there are bound to be times when specific technologies fail and research paths lead nowhere, and project goals have to be changed. It would be inefficient if each of these changes had to meet with congressional approval. That is not what is suggested here. Rather, only the large program directions need to be reviewed. These are the directions for which changes could result in substantial increases in program costs, or could lead to the development of technology that cannot meet reasonable public acceptability criteria. Since the Congress, through the legislative process, plays a large part in implementing public acceptability in most matters important to society—e.g., environmental—one principal benefit to be gained by oversight of the HSCT program would be consistency among public policy decisions.

FOLLOW-ON DECISION

As early in the research and technology program as possible, the Congress may wish to begin exploring options for further aircraft development in the event the validation stage is successful. This would include examination of possible demonstrations required, production of a prototype aircraft and different paths to eventual commercial development. As described above, there is considerable doubt in the domestic industry that they will be able to produce a commercial aircraft on their own, no matter how successful the research and technology program may be. A possible way to analyze these options would be to request such a study from the Congressional Office of Technology Assessment or the National Academy of Engineering. In addition, it may be useful to request NASA to examine this question.

The distinct possibility that international cooperation will be required to develop a commercial HSCT means that examination of whether and how this might be achieved should begin soon. The Congress may wish to direct the executive branch in cooperation with the various industries involved to begin exploring with potential international partners the framework in which such efforts might take place. This would be especially important if some kind of participation in the research and technology phase were needed as part of any development agreement.

Another option for commercial development assistance may be a Federal Government purchase of several aircraft. If this is so, it is quite probable that the Department of Defense—one likely buyer—would have to be involved early on in the research and technology program. The Congress may wish to consider whether this option would be cost effective and how it might be done in order to ensure smooth transition to a DoD purchase without compromising the commercial requirements of the HSCT.

APPENDIX A

ATTENDEES—CRS WORKSHOP ON HIGH-SPEED CIVIL TRANSPORT

MAY 24, 1988

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